DEVELOPMENT OF PLATFORM

A I M

(ASSESSMENT, INSPECTION, MAINTENANCE)

PROGRAMS

PHASE II

JOINT INDUSTRY PROJECT

FINAL REPORT

BY

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EXECUTIVE SUMMARY

The AIM-II project has demonstrated application of the AIM-I approach to assessment and requalification of existing platforms. This demonstration involved AIM engineering analyses of two actual platforms provided by project participants. These platforms provided the study with a variety of realistic problems typically associated with older platforms.

Platform "A" is a five-leg tender drilling platform installed in 1963 in the central Gulf of Mexico in 140 feet of water. The structure supports nine gas wells, has a projected remaining economic life of 12 years, and is unmanned. Recent extensive condition inspections disclosed a wide variety of damage and defects in the structure. AIM evaluations of this platform indicated that if the structure is to be replaced in the event of failure, then the best cost-benefit alternative is to raise the deck and repair current damage. In the case of non-replacement, the best commercial alternative is to leave the platform "as-is" in the damaged condition. Evaluations of the platform "risk" levels for these AIM alternatives indicate the risks are within a marginally acceptable range.

Platform "B" is an eight-leg tender drilling platform installed in 1959 in the central Gulf of Mexico in 52 feet of water. The structure supports seven oil wells, has a projected useful economic life of 5 years, and is unmanned. Recent condition surveys have disclosed a limited amount of damage to the structure. AIM evaluation of this platform indicated that wave load management (remove unnecessary boat landings and marine growth) is the best alternative for both the platform

replacement and non-replacement options. Evaluation of the platform "risk" levels for this AIM alternative indicate the risks may exceed marginally acceptable levels.

The AIM-II example demonstrations highlighted two key implementation problem areas. The first regarded engineering analyses of platform capacities or Ultimate Limit State (ULS) resistances. ULS analyses is required since it provides the only consistent basis of performance throughout the platform's life. However, these types of analyses currently require specialized analytical tools and experienced personnel. ULS analysis can be time consuming and costly to implement.

The second problem area regards the processes for determining, justifying and communicating acceptability of a platform AIM program or suitability for service, with particular concerns for the public regulatory processes. There are currently no industry or regulatory recommendations or guidelines for establishing acceptable risk levels. As demonstrated by these example applications, the most attractive commercial alternative does not always reflect the most attractive risk-based alternative.

It is the authors' opinion that ample understanding and engineering technology exist to solve these two key problems. This understanding and technology need to be developed into a form suitable for <u>routine</u> industry and regulatory applications. Such efforts represent a developing maturation of the AIM approach, leading eventually to definitive engineering guidelines for the requalification of existing offshore platforms.

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1.0 INTRODUCTION

1.1 Background

This report summarizes results of the second phase (AIM II) of an industry sponsored study to develop AIM (Assessment, Inspection, and Maintenance) programs for existing platforms that are defective or have experienced damage. The first phase (AIM I) outlined an integrated, general, and non-prescriptive AIM approach. The second phase (AIM II), described in this report, illustrates an application of the AIM approach through evaluations of two example platforms.

The Phase I AIM study was coordinated and funded by the Minerals Management Service (MMS) Technology Assessment and Research Branch. The project was performed by PMB Systems Engineering Inc. (PMB). The project was assisted by an advisory panel of 18 industry representatives. The panel was organized to ensure that industry guidance was integrated into the effort. This project developed in general terms a practical engineering approach to assist in definition and implementation of AIM programs for offshore platforms. The results of the Phase I study are documented in a comprehensive final report [1] and a progress report [2]. The results of AIM-II are documented in two progress reports [3,4] and this final project report.

The AIM approach is one that attempts to establish the integrity of a structure, or resolve problems with it, at the least possible cost. The AIM approach is incremental, addressing the most serious problems first. An important part of the approach is providing information to assist with the management of uncertainties that are associated with requalifications. These uncertainties arise in the expected future loadings on the platform, accuracy of predictions of platform performance (capacity) and evaluation of alternative maintenance or modification programs.

The Phase II study was conducted and funded by the MMS (major contributor) and 17 other industry and government participants. In this phase, the AIM approach formulated in Phase I was demonstrated by performing engineering AIM analyses of two example platforms. Information about the example platforms and their related service histories were donated to the project by the project participants.

The AIM II project provided a proving ground for testing the current industry technology available for AIM assessments. The project provided a forum for gaining insights into the strengths and weaknesses of both the AIM approach and the supporting evaluation procedures.

1.2 Objectives

The primary objective of the AIM-II project was to demonstrate and document application of the AIM-I approach. This demonstration involved AIM engineering analysis of two candidate platforms provided by project participants. These platforms provided the study with a variety of realistic problems typically associated with older platforms.

The application of the AIM approach to real platforms provided the study with technical and political problems that might not have surfaced if a "hypothetical" platform had been used in the study. The use of real platforms also allowed an unbiased application of the AIM approach, rather than the case of a hypothetical platform where certain unforeseen biases may enter the system in order to project results or outcomes in a particular direction.

These realistic problems also introduced controversial topics that provided a focus for discussion and comment from the project participants. In a hypothetical system, these topics might have been intentionally avoided or constrained out of the system.

The AIM-II example platform analyses had two basic purposes. The first was to illustrate one way that the non-prescriptive AIM-I approach could be applied to an engineering evaluation of alternative AIM programs for low consequence, (unmanned, low pollution potential) older platforms in the Gulf of Mexico. Such structures are representative of a large majority of Gulf of Mexico structures being requalified.

A second purpose of AIM-II was to highlight technical areas where the AIM approach could be deficient. The deficiencies could be those regarding the desirable attributes of the approach (simplicity, consistency, etc.), or the engineering technology to implement the approach.

1.3 Results of AIM-II

AIM-II developed three major products:

1. A demonstration of how two realistic structures could be evaluated using the AIM-I approach and how definitive recommendations could be developed on viable AIM programs. The emphasis was on the processes of evaluations and reaching decisions, not on the details of analyses, nor on the results of the analyses.

2. A forum for open discussion and deliberation of the key problems and aspects of developing AIM programs for platforms. The AIM-II meetings were instrumental in introducing a number of important concepts and approaches, particularly in making engineering evaluations of platform loadings and capacities and evaluating alternative AIM programs. An attempt has been made to incorporate those participant contributions and insights into the revised AIM-I report [1] and the AIM-II examples.

3. An identification of the key problem areas associated with implementation of the AIM-I approach. Two key problem areas surfaced (Appendix E). The first implementation problem area regarded engineering analyses of the platform capacities or Ultimate Limit State resistances. While the engineering tools and technology are available to perform such analyses, the tools and technology have not been developed to the point where they are suitable for routine, repetitive AIM evaluations. Thus, the

AIM precepts of simplicity and practicality cannot be satisfied with the present state of development of platform capacity analyses.

The second implementation problem area regarded the processes for determining , justifying, and communicating acceptability of a platform AIM program, with particular concern for the public regulatory processes. Alternatively stated, the procedures and criteria for determining suitability for service was the most controversial part of the AIM-I approach. Even for the two low consequence platforms involving no significant personnel injury or pollution potentials, there were extensive debates over how to approach the problem of determining suitability for service. Several industrial (commercial) cost-benefit approaches were identified and implemented in AIM-II. In addition, several historic, practice calibration approaches suitable for public (regulatory) approaches were identified and implemented in AIM-II. However, there was little consensus on the processes for reaching decisions on suitable AIM programs, and even less consensus on the details of evaluations made in industrial and regulatory frameworks. Thus, the AIM-I precept of consistency cannot be satisfied at the present stage of development of procedures and criteria for determining suitability for service.

Several additional technical problem areas were also identified in AIM-II. These problem areas were those of estimating realistic wave forces when the wave crests reached the operating decks of the platforms, and estimating realistic capacity characteristics of damaged (cracked, dented, bent) tubular members and joints. The technology to address these problems has been and is being developed. However, this technology has not been integrated into any consistent and generally acceptable framework for AIM applications. Additional development efforts are required.

The authors' perspective of these problem areas is that they represent areas in which there is ample technology to address the problems in the context of developing good AIM programs for existing platforms. The problems are ones of technology integration and application, experience, and development of consensus engineering procedures and guidelines to perform platform requalification/rehabilitation analyses, and to evaluate results of such analyses. The implication for future work would ultimately be directed toward development of a "recommended practice" for requalifying existing structures.

1.4 Acknowledgments

Figure 1-1 identifies the 18 industry and government sponsors and sponsor representatives who participated in this study. The directions, insights and technical contributions of these representatives are gratefully acknowledged.

The PMB team consisted of Mr. Robert Bea as Project Manager, and Mr. Frank Puskar as Project Engineer. Also participating in the study from PMB were Messrs. David Stewart, Arthur Kalmeyer and Robert Figgers. Mr. Griff Lee and Professor Ben Gerwick acted as project consultants.

Special thanks goes to Mr. Chuck Petrauskas of Chevron and Mr. Gene Berek of Amoco for their assistance with environmental conditions and forces at the two platform locations.

Finally, a special thanks to those project participants who provided the background information on example platforms "A" and "B".

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• Elf	- Yves Guenard
• Marathon	- Ron Antes
• Exxon	- Hugh Bannon
• McDermott	- Jay Wilkins - Griff Lee
• Minerals Management Service	- Charles Smith - John Greggory - Felix Dyhrkopp
• Mobil	- Clair Menning - Zane Bolen - Gene Kuhn - Frank Dello Stritto
• Phillips	- Roger Thomas
• Shell	- Pete Arnold - Peter marshall - Pat Dunn - Jim Robinson

AIM II PROJECT PARTICIPANTS

FIGURE 1-1

• Statoil	- I. Langen - Brigt Hatlestad
• Texaco	- Lynn Fleury
• UNOCAL	- Michael Craig - Mike Isenhower

AIM II PROJECT PARTICIPANTS

FIGURE 1-1

(Continued)

2.0 APPROACH

2.1 AIM Process

The fundamental steps of the AIM approach are identified in Figure 2-1. Detailed explanations of the steps can be found in the AIM I report [1]. The steps are summarized here as follows:

1. **Identification** - Selection of a candidate platform.

2. **Condition Survey** - Formation or continuance of a data bank containing all pertinent data on the platform.

3. **Screening Defects** - Assess platform for significant defects. With no defects, design next AIM cycle. With defects, determine if mitigation is necessary.

4. **Mitigation** - Prioritize the defects to be remedied and identify practical remedial alternatives.

5. **Evaluate Alternatives** - Develop and review rehabilitation alternatives.

6. **Implement Mitigation** - Design/engineer alternative.

7. **Engineer the Next AIM Cycle** - Design/engineer and implement the next inspection and maintenance cycle.

The AIM approach outlined in the Phase I study attempts to focus on a clear and logical path for reevaluating existing offshore platforms. It is intended to be a simple approach that develops acceptable results with minimal effort and costs. It must also be compatible with existing offshore platform systems, yet versatile enough to handle future systems and currently unforeseen problems. An important aspect of the approach is that it is intended to provide consistent results for similar problems when used by different engineers.

The concept of simplicity with consistency poses many problems in the early development stages of an approach such as AIM. To remain simple, the approach requires the use of assumptions, approximations and judgment-based decisions that may vary between investigators. Yet oversimplification may unnecessarily tax some platform systems, and more seriously, simplification may overestimate the performance of other systems. In terms of consistency, a rigorously outlined procedure for AIM assessment may perhaps provide consistent results between investigators; however, the approach would likely be complex in nature (to ensure the approach is capable of covering all aspects of platforms) which violates the simplicity aspect of the process.

The Phase I AIM study looked at the AIM approach in the general sense and did not detail specifics of the procedures required throughout the analysis. This was intentional, since the goal of that study was to first obtain industry consensus on an acceptable approach, and then to describe in general terms the processes of the approach. It is the aspect of the procedures and their application that this study addresses. The study shows applications of the AIM approach, with the intention that the applications are not the prescribed approach nor are they the best approach. They are interpretations of the AIM process, and are meant for illustration, comment, and criticism.

2.2 Procedures

The previous section described the general approach involved in the AIM analysis. This section will discuss the procedures required to carry out the AIM approach. The general intent of each procedure will be the same for all operators (e.g. evaluate platform capacity); however, the exact methodology required to implement each procedure is up to the operator (e.g. nonlinear overload analysis or simple limit state hand calculations to determine platform capacity).

The procedures described in this section are an interpretation of AIM by PMB. The best techniques available to PMB were used to step through the AIM approach. Simplification was utilized in some areas where more sophisticated techniques were deemed nonproductive. Simplification was only utilized where past experience has demonstrated that more elaborate techniques were not required.

It is not the intent of this study to propose the exact procedures for AIM analysis, but rather to demonstrate how the process works through realistic examples. The development of recommended procedures, and perhaps simplistic methods for AIM analysis, is the intent of future AIM related studies.

Figure 2-2 shows in more detail the procedures of the AIM approach. The major elements are Structure Characterization, Evaluate Future Demands (loadings), Evaluate Capacities (present and future), Evaluate Consequences of Failure, Evaluate Alternatives, and Implement Alternatives. These procedures are described in the following paragraphs.

Structure Characterization involves the gathering of accurate platform related data. This includes design, construction, installation, environmental, operating and maintenance histories. For many older platforms, this type of information is not readily accessible and can be difficult (if not impossible) to obtain. Also of importance is the identification of exceptional events or developments during the platform history (e.g. collisions, additional wells, workovers, large storms through the region). This data can be stored in a computerized data base (preferable for future AIM work), or in hardcopy (paper) files, as in this study. This is the most important part of AIM since everything from this point forward is dependent on the validity and completeness of this data base.

Evaluate Future Demands involves assimilation of environmental and operational data and assembly of expected future platform loadings. This information should include some format of uncertainties (e.g. return period of event, weighting factor) that defines the likelihood of occurrence of a load. This is also true on the operation side were there is a likelihood of adding more wells or increasing topsides weight. Future environmental demands for this study were dependent upon return period (keyed to the wave height) with loadings determined by a 3-D spatial computer model and the Morison equation.

Evaluate Capacities involves some form of ultimate limit state (ULS) analysis for the platform. The evaluation of platform capacity based upon ULS provides the only constant basis for platform life cycle comparison (see Appendix E, Letter from G. C. Lee). Re-evaluation of the platform (during different stages of its life) using design techniques and guidelines would provide a range of results that depend upon techniques used for determination of platform loads (e.g. C_d and C_m fctors) and material and strength coefficients used for member design (e.g. API code checks). These factors and codes are modified and revised over time, resulting in an inconsistent evaluation of the platform during different stages of the platform's life cycle. On the other hand, ULS analysis does not include any inherent design or safety factors and should provide consistent comparisons during the platform's life cycle.

This study used the inability to carry topsides loads as the ultimate limit state (i.e. failure). This limit state was said to be achieved at the value of lateral loading due to wave, current and wind forces causing failure. Other analyses may use a specific measure of deck deflection or rotation to define the limit state. This state must be characterized for the present and future (AIM alternatives) configuration of the platform.

Evaluate Consequences of Failure involves both engineering and management input. Engineering input may be in the form of determining site restoration and platform replacement requirements. Management input may be somewhat more subjective in nature since it may deal with the political implications of environmental damage or personal injuries. Management must also determine if the platform will be replaced in the event of a failure.

Evaluate AIM Alternatives is the next procedure. At this point, all information is available and the investigator uses available procedures to combine the data and make a reasonable assessment of the AIM alternatives. This study used first approximation probabilistic methods for the AIM evaluation. More exact methods may be as equally acceptable, but it is believed the results would be similar in nature.

Implementing the AIM Alternative is the final procedure of the process. This step includes the designing/engineering of the "best alternative" and implementing it into the platform operations. The results of the implementation are included into the platform's data bank (Structure Characterization).

This section has provided a brief review of the key AIM procedures and has noted the methods used in each procedure for this study. Further details of each procedure are provided in related subsequent sections of this report. It was felt it would be best to discuss these techniques in detail in the individual sections where readily available examples provide clearer explanation of the technique.

2.3 Candidate Platforms

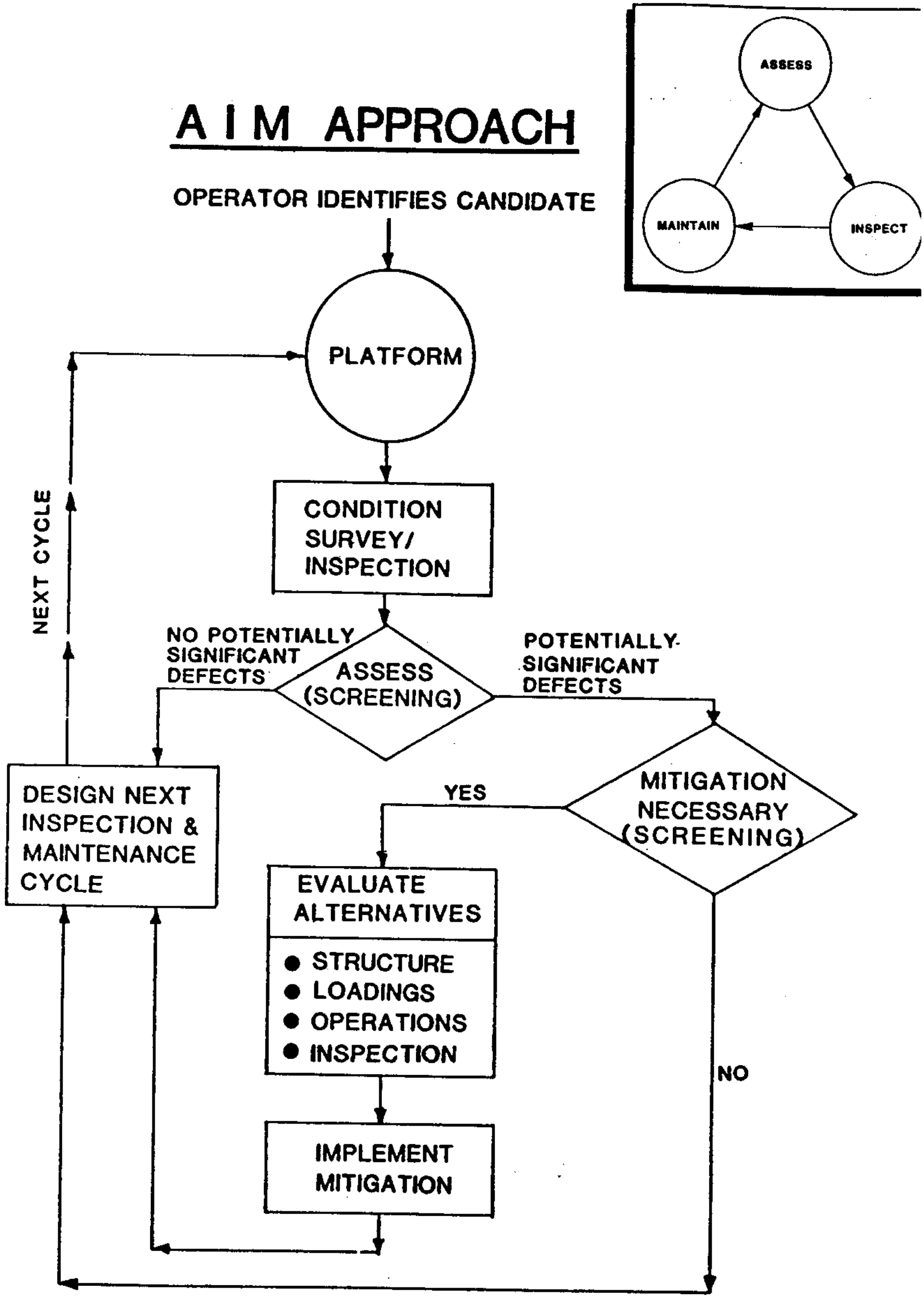
The use of actual platforms with their design-construction-operation histories provides a demonstration of the AIM approach under realistic conditions and with realistic problems. Actual platform data provides challenges that might otherwise be eliminated as too difficult or perhaps irrelevant in a study using a hypothetical platform and related data. The results of a study using hypothetical data might then become questionable and might not fully illustrate the AIM process. In addition, an underlying purpose of this study is to learn the strengths and weaknesses of the investigative and analytical tools available to the industry for preforming AIM assessments.

Two platforms were selected for demonstration of the AIM approach. Both platforms are situated in the Gulf of Mexico, with each platform in service for more than 25 years. They are typical of the many older platforms that currently exist in offshore waters and are in need of reevaluation. In order to protect the identity of the platforms, they have been designated as Platform "A" and Platform "B". Non-essential (to this project) sensitive and proprietary details such as organization, contacts, platform names and locations, and other similar information has not been cited or documented per request from the participants who donated the platform information used in this study.

Platform "A" is shown in Figure 2-3. This tender drilling and production platform was installed in 1963 in the central Gulf of Mexico in 140 ft. of water. The platform has four corner legs plus a center leg. The nine wells are located in the center of the platform. The five piles are ungrouted and penetrate 170 ft. into stiff silty clays. The topsides consists of two major deck levels plus a sump deck and is unmanned. The platform was recently inspected by divers and found to have considerable damage including a missing member, separated members and numerous cracks. The platform has a projected future life of 12 years.

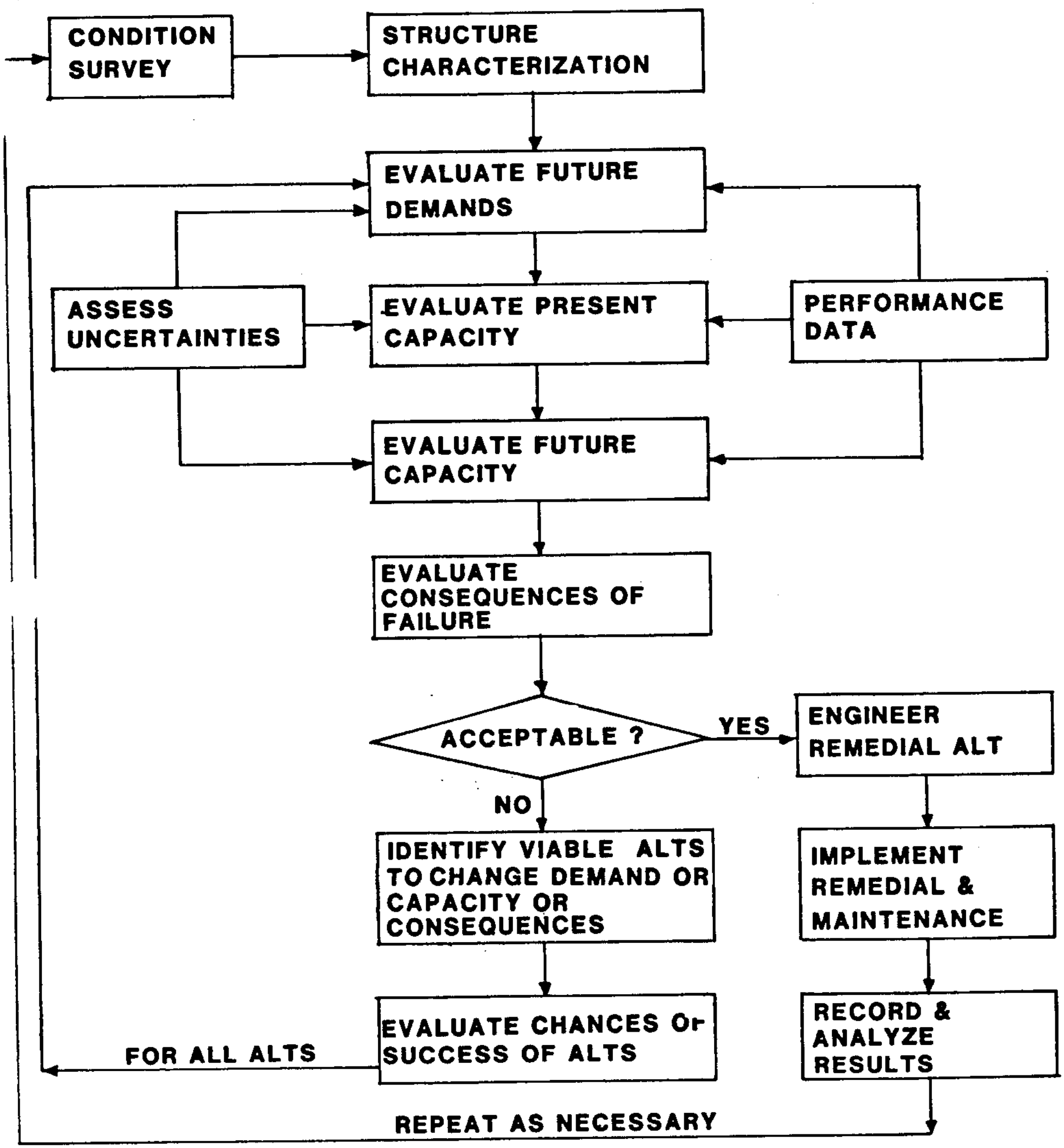
Platform "B" is shown in Figure 2-4. This structure is also a tender drilling and production platform located in the central Gulf of Mexico. The platform was installed in 1959 in 52 ft. of water. The platform has eight legs with grouted piles penetrating 125 ft. through stiff clays and finally bearing on a layer of dense sand. Five original wells are located in the center of the jacket and two recently added wells are located outboard of the jacket. The topsides consists of two deck levels and is manned only during the daylight hours. A recent diver inspection found a limited amount of damage including a severed horizontal near the waterline plus a few dents and cracks. The platform has a projected future life of 5 years.

These two platforms provide excellent background for a first implementation of the AIM process. Platform "A" is relatively simple in design with a symmetric configuration and equivalent loading from all directions. It is significantly damaged with missing, separated and cracked members. It is the first platform discussed since its simplistic geometry and loadings produces more opportunity for discussion of the AIM procedures rather than the platform itself. Platform "B", on the other hand, is more complicated having unsymmetric geometry requiring ultimate capacity analysis from different directions. It is in shallow water posing breaking wave problems and its proximity to the coast results in different loadings from different directions. It is the second platform discussed, with more effort spent describing the platform's performance rather than the AIM procedures (which are thoroughly described for Platform "A").



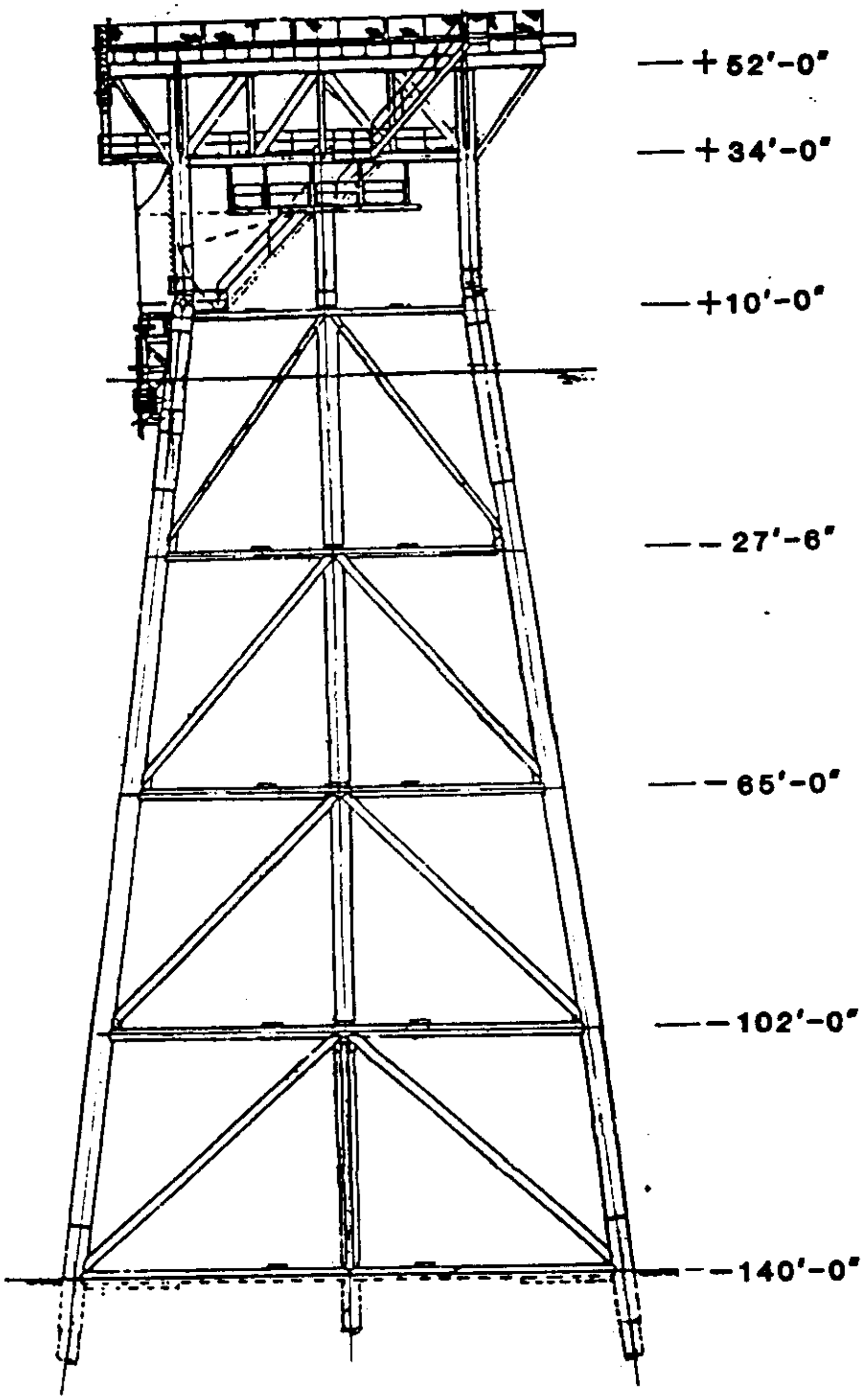
AIM APPROACH

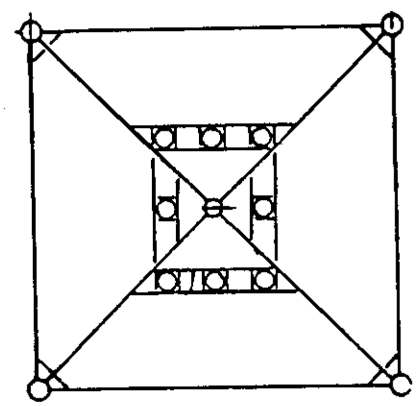
FIGURE 2-1



AIM PROCEDURES

FIGURE 2-2

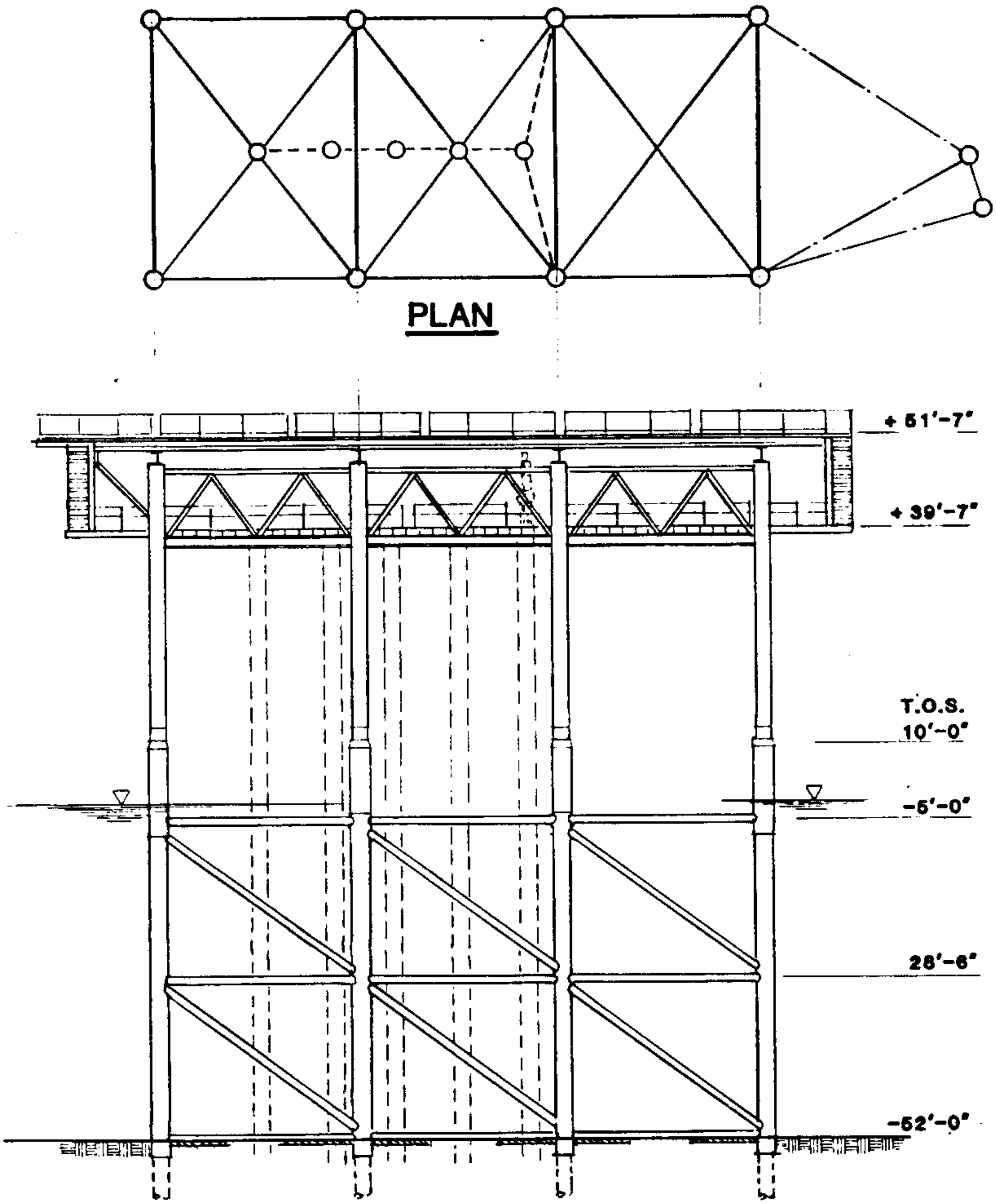




PLAN

PLATFORM "A"

FIGURE 2-3



PLATFORM "B"

FIGURE 2-4

3.0 PLATFORM "A"

This section describes the AIM process as applied to Platform "A". The section describes the basic procedures, key points and key results of the process. Further details of the evaluation are provided in Appendix A - "Platform "A" Evaluation."

3.1 Background Information

Figure 3-1 shows Platform "A" and describes some of its key features. Included in this figure are installation date, water depth, geometry and member sizes, soils, topsides and remaining economic life (Appendix A provides an expanded form of this data). The platform has down-hole automatic shut-in equipment installed in the wells. Recent diver inspections of the platform turned up a wide range of damage as shown in Figure 3-2. There is a missing interior vertical diagonal member, three members are completely separated (severed), and there are numerous cracks in other members.

In general terms, the platform is about 25 years old, is symmetric in shape, has ungrouted legs/piles with no joint cans on the legs, is currently severely damaged (basically 4 members completely ineffective) and has a 12-year remaining economic life.

Based upon this preliminary information, the platform has been chosen as a candidate for AIM assessment.

The first AIM task is to gather all pertinent information related to the platform. This is accomplished by collecting data from the platform's engineering and operating groups as well as the original design vender. This information is assembled and sorted and key facts and figures about the platform are recorded for future use.

The general characteristics of the platform are shown in Figures 3-1 and 3-2 with more data provided in Appendix A. Environmental data is also collected for the location as described in the following section.

3.2 Environmental Conditions

The two prime environmental conditions assessed for the site were oceanographic data and geotechnical data. These sets of information were developed from public and proprietary information [5 - 38] as well as input from several of the project participants, with the results summarized in the following paragraphs. All data was corrected for local effects at the platform site, such as water depth and coastal proximity.

Wave height, wind speed, storm surge and current speed information was developed for the site. Figure 3-3 shows the wave height versus return period for the site. The wave height increases with return period until a height of about 100 ft. is reached (10,000-year return period) which is the theoretical maximum height for the Gulf of Mexico region. The platform, installed in 1963, appears to have withstood the effects of Hurricane Hilda (1964) with a maximum wave height (at this site) of 56 ft. and a return period of about 60 years.

Details on the wind speed, storm surge (astronomical tide included) and current speed are provided in Appendix A. This data was developed such that the wind, surge and current are those that coexist during the same return period wave height (Figure 3-3). The waves, wind and current were assumed to act colinearly and can equally attack the platform from any direction.

The Stream Function Wave Theory was used to determine the wave profile and water particle kinematics. The wave period was selected to provide a wave steepness (ratio of wave height to length) of 1 on 12 which is representative of hurricane conditions. Figure 3-4 shows the wave crest elevation versus return period as predicted by the Stream Function. The data was developed using the wave height and storm surge data for each return period. The wave is seen to impact the lower deck at about a 33-year return period.

Morison's equation was used to compute wave forces on the platform. The drag coefficient was set as 0.7. An additional set of analysis was also run with the drag coefficient set to 1.0 for marine growth roughened tubulars, and 0.7 for tubulars without marine growth. This provided a variation on the drag coefficient to determine its effect on the AIM evaluation. Member diameters were increased to account for marine growth. Hydrodynamic forces were computed for water particle kinematics normal to a member.

Based on this selection of drag coefficients, the current was not explicitly included in the force computations (i.e. current velocity not added to wave particle velocity [34,39]). Thus, the current was assumed to be implicitly included in the force estimation in terms of the C_D and is offset by other factors not explicitly accounted for by the analysis (e.g., directional spreading).

For the case of a wave in the deck, the drag coefficient was set to 2.0 for most members and equipment in the deck [38]. The inertia coefficient was held constant at 1.5 for all cases.

The standard API RP 2A formulation (Eq. 2.3.2-1, 17th Edition [39]) was used to compute aerodynamic forces on the deck. The wind drag coefficient was taken as 1.0 for clean decks, 1.5 for cluttered but not "blocked" decks, and 2.0 for blocked decks allowing little or no light passage. Wind forces were disregarded when the wave crest was in the deck.

Figure 3-5 shows the general soil conditions at the site. This "log" was assembled from a boring taken at the site and from information from other borings at nearby sites. The soils are characterized by a 10-ft. thick layer of soft clay overlying stiff clays.

3.3 Environmental Forces

The computation of environmental forces, predominately waves, can be accomplished by a variety of methods. Forces can be hand-calculated for a one foot diameter member extending through the water column and then the global force can be approximated for an entire structure assuming the legs are the major contributors of force (plus some percentage increase to account for loads on braces). Another method is force computation according to a single set of kinematics at the center of the structure which are then used on all members (legs and braces) to compute wave forces. Still another method (used by this study) is the spatial variation of members along with two-dimensional spatial variation of wave kinematics.

The type of environmental force computation depends somewhat on the uses for the environmental forces. In this study the forces will be used in two ways -- first to compute maximum total global force versus return period, and second to use as a force profile that is applied to the platform for the overload analysis. Figure 3-6 shows in more detail how the force results are used in this study.

A linear or nonlinear platform analytical model is first developed for computing the wave forces. The model can be linear since the results at this stage are dependent only on the member geometry and not on strength. The wave is then stepped through the structure (twenty increments per wave cycle for this study) and the maximum total (summed over all members) base shear for a wave cycle is recorded as well as the wave forces acting on each member at that time. The loads acting on each member are distributed to the end nodes which define the member. The resulting force file is therefore a set of lateral loads applied to each of the nodes (in the wave zone) in the platform.

The maximum base shear and the return period of the wave are used to generate a graph similar to that shown in Figure 3-7. The load in the platform is seen to increase with return period at a moderate rate (approximately as the square of the wave height) and then take a substantial increase as the waves start acting on the deck. This sudden increase is due to the waves acting on the deck framing and equipment which provides a large frontal area for generating wave forces. If the deck did not exist (or if the deck was "raised" as an AIM alternative) the the force would continue on the indicated (dashes) trend. As shown in Figure 3-6, this load vs. return period data is used in later evaluation procedures of the AIM process.

The wave force profile (i.e. lateral loads at each node due to a specific wave) is used to continually load ("ramp") the platform until failure is achieved. The wave which is just under the deck is the wave profile used for the analysis. As shown in Figure 3-6, the results of the platform failure analysis (details to be discussed in Section 3.4) are used later in the evaluation procedures.

Figure 3-8 shows a perspective view of the 3-dimensional SEASTAR [40] computer model for Platform A. At this point, the model contains only the geometric features of the platform (member location, length, diameter and hydrodynamic coefficients) since the current purpose is to only determine wave loads. The deck framing is modeled in some detail with modeled members incorporating the wave area for members not explicitly modeled. The deck equipment is distributed along the major horizontals at each deck elevation.

Figure 3-9 shows the wave force profile developed for the wave just below the lower deck (33-year return period). The profile is constructed by summing the nodal loads at each horizontal elevation. The profile bulges at a location just above the water line due to appurtenances such as boat landings, barge bumpers, and walkways. The total force on the platform for this return period is about 750 kips.

Figure 3-10 shows the completed results of the environmental force analysis to determine force versus return period. The range of forces for a drag coefficient of 0.7 and 1.0 are shown. The analysis was run for the case with and without the deck. For the case without the deck, the same computer model was used except for elimination of wave areas for the deck framing and deck equipment computer elements.

The waves to the right of the vertical line at the 33-year return period are waves that are into the deck. The dashed lines indicate the actual results of the wave force analysis. The analysis shows that waves that are just a fraction into the deck result in a sudden finite "jump" in the total force curve. This is caused by the limitations in discrete element computer modeling, where the wave area for the deck equipment is lumped onto the horizontals at each deck. Thus as soon as the wave crest, with its high water particles velocities, is into the deck, the computer model considers all of the deck equipment to be loaded by the waves. In reality, only a small portion of the equipment would be loaded by the waves. The model could have been further refined to create a smooth transition by adding extra wave elements for the deck equipment, but there would have still been a "jump" of some degree.

Therefore, it was decided to create a smooth transition between a wave below the deck and a wave into the deck by interpolating a straight line between the deck elevation (+34 ft.) and an elevation two-thirds into the lower deck (+46 ft.) corresponding to a 170-year return period wave (Figure 3-4). Therefore, it is logical to return to the computer generated force curve at this point. The two-thirds of deck height was selected because most of the equipment would be completely covered by a wave of this height.

The resulting final force versus return period curve for the platform is indicated by the shaded region. Wind load (12 k for 5-year and 35 k for 33-year return period) has been added to the wave force for waves below the deck. As previously indicated in Figure 3-7, the force curve is seen to increase with return period and then take a substantial increase as the waves start acting on the deck. The upper and lower bounds of the shaded curve reflect the variations in drag coefficient.

3.4 Platform Capacities

The wave force profile discussed in Section 3.3 is used for the overload analysis to "push" the platform until failure or the ultimate state is reached. For this study, it was decided to use the profile for the wave just under the deck (33 year return period) for the analysis. The selection of just one profile was required since overload analysis can accommodate the ramping (i.e. continual increasing of load) of just one load profile at a time.

As shown in Figure 3-11, the process begins by applying the wave force profile (wave just under deck) in one-tenth load increments, until a load factor of one, or full wave under the deck is achieved. If the platform should survive this loading without failure, another load segment is applied where the deck is also being loaded by waves. This load is input as a single load vector acting at the elevation of the lower deck. The load is equally applied to each leg node at this elevation.

At this point, both the wave below the deck and the wave in the deck profiles are increased at the same time until platform failure is reached. The total base shear on the platform at that time is then tracked back to the base shear versus return period information (Figure 3-10) to determine the return interval event associated with platform failure (as defined in Section 2.2 for this study, the inability to carry topsides load).

Figure 3-12 shows how a typical platform responds during the overload analysis. The platform initially responds in a linear fashion as the elements are first loaded. There may be a small amount of nonlinearity at this stage due to deformations in the soils. The response then begins to flatten as members in the platform begin to reach their ultimate load-carrying capacity. The members fail by buckling or yielding in compression, yielding in tension and yielding in bending. These member failures basically decrease the stiffness of the platform, causing it to incur greater displacements for a given force. The result is a flattening of the force displacement curve. A change in the character of the applied force may also change the shape of the curve (e.g. application of large magnitude wave forces on the deck). Finally, the platform can take no greater horizontal loading and failure occurs.

In order to most properly capture the ultimate capacity of the platform, a nonlinear computer model must be developed. This model contains specialized elements that reflect the limit state behavior of the platform members in terms of limit capacity and post limit performance. These capabilities also require special structural analysis software to control the force applications and load redistributions as the platform members fail. This study used the PMB developed nonlinear computer program SEASTAR [40].

Figure 3-13 shows a perspective of the Platform A model and indicates the types of elements used in the various regions of the platform. Also shown are the types of force-deformation for each element. A brief description of the special SEASTAR elements used in the analysis is provided in the following paragraphs. Appendix C provides a more complete description of the computer modeling.

SOILS - PSAS (Pile Soil Analysis System) elements [41]. These nonlinear elements reflect the axial and lateral force-deformation characteristics of the soils surrounding the piles. The shape of the curves follows the recommendations outlined in API RP2A [39]. There are approximately eight PSAS elements for each pile and conductor.

PILES/CONDUCTORS - Nonlinear beam elements. These elements reflect the elastic-plastic relationship for beam-columns that fail by yielding (no buckling). These members are likely to yield before buckling due to their heavy walls and lateral support below the mudline

LEGS - Nonlinear beam elements. Same modeling as piles/conductors.

BRACES - Nonlinear truss elements. The slender brace members are governed primarily by axial loading with very little bending. They are also likely to fail in buckling. Therefore, they are most properly modeled by "strut" elements that carry only axial loads and exhibit a decay in post buckling capacity [42]. However, because of the difficulty in performing a "static" pushover analysis with buckling elements, this project used a nonlinear truss element to model the braces. The nonlinear truss was modeled to provide an elastic perfectly plastic response at the calculated buckling stress for a member. This type of modeling (for the platforms analyzed in this study) is believed to provide a close approximation to the ultimate state behavior of this platform (see Appendix C).

The ultimate stress of each member was taken as the lowest of (1) the member buckling stress under conditions of horizontal wave loading (wave under deck wave with 33-year return period was used to set the horizontal load level), or (2) member punching into the leg (UEG equations [43]). Figure 3-14 shows how these calculations effect a typical brace. Since this structure has ungrouted legs and no leg cans, the second condition of the member punching into the leg prior to the member buckling controlled most braces.

Also shown in Figure 3-14 is the difference between member modeling with the nonlinear truss and the "buckling" strut. Note that for member strength controlled by punching into the leg, as for this platform, the nonlinear truss is perhaps a better modeling tool than the strut. This is because the member will still carry compression loads into the joint after punching.

DECK - Linear beams. Since the deck was modeled to primarily capture wave loads and to distribute loads between legs, the deck members were modeled as linear beam elements. The leg members extending through the deck were modeled as nonlinear beams.

The steel material used throughout the platform is A36 with a nominal yield stress of 36 ksi. This yield value was upgraded by 12 percent to account for the difference between nominal and expected yield strengths [44]. It was increased by another 12 percent to account for strength increases due to strain rate effects [45]. The actual yield stress used to compute member properties was therefore taken as 45 ksi (1.25 x 36 ksi). The intent of this modification is to account for actual in-service expected yield values rather than allowable design values.

Once the platform model has been defined and all member properties have been established, the overload analysis can proceed. As previously mentioned, a static analysis was performed by slowly increasing the loads on the platform until failure was achieved. Since the platform is symmetric in geometry, the analysis was only run in the orthogonal X direction. A more complete study may check overload in several directions and attack angles. It may also consider the introduction of non-symmetry caused by damaged members.

Figure 3-15 shows the deflected shape of the platform just prior to failure. At this point, the full magnitude of the wave below the deck has been applied to the platform and the deck is starting to take load from the deck wave load vector. There is some displacement in the piles but no yielding. The deck is slightly rotated in the opposite direction of wave loading due to the effect of the battered legs.

Figure 3-16 shows the force-displacement history at the deck level for the as-designed condition. The platform is seen to displace in a linear (elastic) fashion at initial loading. The response curve flattens (more ductile) at the the point of application of the wave load acting on the deck. This larger deformation for a given force is due to the application of loads high up on the platform (the loads of the wave acting below the deck were primarily applied along the submerged portion of the platform). Shortly after the application of deck wave loads, the first member (horizontal at +10 ft.) "punches" through the leg. Several other braces reach their ultimate state a short while later, until the legs begin to yield in bending. The leg failure is due primarily to the application of the large wave loads on the deck. Finally, more braces fail until a numerical solution is difficult to achieve signalling the approximate ultimate state of the platform at 1060 kips lateral load.

This information can be used to determine that the platform can withstand 1060 kips of lateral load (for the as-designed condition), or by using Figure 3-10, the environmental forces associated with a 45 year return period event for a 0.7 drag coefficient.

Note that if hurricane Hilda (1964) did develop maximum wave heights of 50 to 55 feet, and these waves acted on the platform, then maximum lateral forces in the range of 1000 to 1200 kips would have been developed. Given an intact platform ULS capacity in the range of 1000 to 1100 kips, the platform should have shown signs of nonlinear behavior. Unfortunately, there are no inspection reports immediately following Hilda to indicate the validity of this experience/calibration point.

Note that if the original design force (base shear) of approximately 600 kips were used to define the capacity, there would be a dramatic underestimate of the platform's lateral load-carrying resistance.

Similar analysis are performed for the structure for the AIM alternatives investigated in this study. The alternatives and related analysis can be summarized as follows:

Alternative 1: As-Is. Leave the platform as-is with the damage as described in Figure 3-2. This requires modification to the platform computer model to reflect the missing and damaged members (see Appendix C, [56]). Figure 3-17 shows the result of the damaged overload analysis. The initial stiffness of the structure is lower (due to the missing and separated members) and several members yield at lower load levels (first kink in plot). The ultimate state of the platform in this condition is 950 kips. This load level corresponds to a 42-year return interval event (Figure 3-10, C_D = 0.7).

Alternative 2: Repair platform to as-designed condition. Repair all damage to the platform. This results in a limit state capacity the same as the as-designed condition shown on Figure 3-17 to be 1060 kips. This load level corresponds to a 45-year return period event (Figure 3-10, $C_D = 0.7$).

Alternative 3: Repair damage and grout legs. The as-designed computer model with modified leg punching was used for this analysis. The leg punching was modified to account for the grout between pile and leg which helps increase the ultimate punching load. This typically added sufficient strength to cause the member to buckle prior to leg punching. The leg and pile elements were also modified to reflect composite action caused by the grout. Figure 3-17 shows the results of the ultimate capacity analysis. The platform is initially stiffer due to the composite action of the pile-leg. The platform response flattens fairly quickly after the application of the deck wave loads, with ultimate capacity reached at 1155 kips. This load level corresponds to a 50-year return period event (Figure 3-10, $C_D = 0.7$).

Alternative 4: Raise deck and make all repairs. The as-designed computer model was used for this analysis. Since this case does not consider waves in the deck, only the wave profile forces were continually increased for the analysis. Figure 3-17 shows the response of the platform. The response does not flatten like the other curves since the deck is considered to be above the waves. The first kink in the response is caused by member brace failures until complete platform failure (primarily braces) at a loading of 1440 kips. This load level corresponds to a 180-year return period event (Figure 3-10, w/o deck, $C_D = 0.7$).

3.5 AIM Alternatives Evaluation

The AIM approach suggests two frameworks for making evaluations of alternative AIM programs: (1) Industrial (Commercial) Cost-Benefit Framework, and (2) Public (Regulatory) Historical, Standard of Practice, Calibration framework. The approach emphasizes the processes for reaching decisions on suitability of a given structure, for a given AIM cycle and program, and for a projected service/operations life (suitability for service). The complementary nature of the two frameworks is emphasized. Within these two frameworks, the differences between unmanned, low consequence potential platforms (like platforms A and B), and manned high consequence potential platforms can result in very different evaluation processes and problems.

3.5.1 Cost-Benefit Evaluation

This section discusses a cost-benefit evaluation of AIM alternatives for Platform A. This evaluation attempts to identify the most promising AIM alternative based upon economic considerations. This platform is unmanned and has down-hole automatic shut-in equipment installed in the wells.

The basic premise of this cost-benefit evaluation is that the best alternative is one that produces the lowest total expected cost. Expected total cost is composed of expected initial costs plus future costs:

$$E\ (C) = E\ (I) + E\ (F)$$

Initial costs include all costs to modify the platform for the AIM alternative plus all costs associated with future platform maintenance designated by the AIM alternative. Initial costs can include structure repair and modifications, operations (remove equipment, temporarily halt operation for repair work), engineering (AIM assessment, remedial engineering) and inspections (current and future planned).

Future costs include all costs associated with loss of serviceability (failure) of the structure including [46]:

A. Costs Associated with Net Revenues

   1. Expected Losses Due to Deferred Production

   2. Expected Lost Production Costs

B. Restoration Costs

   1. Salvage Costs

   2. Costs of Plugging Wells

   3. Pollution Abatement and Cleanup

   4. Human Life Loss (Injuries)

   5. Other Impacts (Political, Regulatory, ...)

C. Replacement Costs

   1. Platform Replacement

   2. Equipment Replacement

   3. Costs of Redrilling Wells

Based on evaluations made by Stahl [47], the following summarizes estimated future costs for self-contained drilling platforms in the Gulf of Mexico and North Sea. Note that the future costs are normalized by the platform's initial construction cost (not including wells and equipment).

Future Cost Category	Cost Ratio = Cost/Platform Initial Cost
Gulf of Mexico Platform	
Restoration	1.03
Replacement	5.14
Net Revenues Per Year	4.29
North Sea Platform	
Restoration	1.00
Replacement	2.28
Net Revenues Per Year	4.20

The expected potential future costs are taken to be the product of the future costs and the likelihood (probability) of experiencing these costs.

Figure 3-18 summarizes the expected AIM initial costs estimated for Platform A. The details of these costs are provided in Appendix D. The structure repairs and modifications depend upon the selected AIM alternative. Since none of the AIM alternatives require modified operations (e.g. reduced deck equipment), the incremental operations costs are zero (operation costs associated with the raise-the-deck option are included in the cost figure quoted in item "A"). Engineering costs (AIM and other) have been estimated at $100,000. Extensive inspections are slated for the platform every two years since the platform is known to exhibit some damage history.

The interval and extent of inspections can vary according to the AIM alternative. For example, an alternative that greatly increases the platform capacity may require fewer future inspections than one that leaves the platform as-is. For the purposes of this study, the same type and interval of platform inspection is held constant for all Platform A alternatives.

Figure 3-19 compares the total initial AIM costs for each of the four alternatives. Alternative 1 (As-Is) provides the lowest initial cost while Alternative 4 (Repair and Raise Deck) provides the highest initial cost.

Figure 3-20 summarizes the potential future costs for Platform A. Net revenues due to lost production are assumed to be zero (e.g. due to increased value of deferred production or due to tax write-down of abandoned reserves). Restoration costs are included here as a future cost. Replacement costs are the greatest contributor to future costs. The decision to replace the platform or not will be a function of the reservoir productivity and economics. This example considers both replacement and non-replacement scenarios.

Figure 3-21 shows an example computation of total costs for AIM Alternatives 1 (AIM-1) through 4 (AIM-4). The example assumes a 12-year remaining life (Figure 3-1), platform replacement in the event of failure and a best estimate C_D of 0.7. The AIM-1 initial cost is seen to be $0.4

M (Figure 3-19). The platform's ultimate capacity for this alternative is 950 kips (Figure 3-17). The return period associated with this ultimate capacity is 42 years (Figure 3-10) (C_D = 0.7). The future cost is the sum of the restoration cost ($3.3 M) plus the replacement cost ($26.9). The total cost is computed as the initial cost ($0.4 M) plus the annual probability of failure (1/42) times the remaining platform life (12 years) times the cost of failure ($30.2 M). The assessment for AIM-2 follows in a similar manner.

The total AIM costs as a function of the Ultimate Limit State (ULS) platform capacity are shown in Figure 3-22 for the case of platform replacement. AIM-4, repair and raise the deck, provides the lowest total cost. This result is the same for a C_D of 0.7 or 1.0. Thus the change in drag coefficient appears to have little effect on the cost-benefit evaluation.

Figure 3-23 shows similar results for the case without platform replacement (abandon in event of failure). For this condition, the most attractive AIM alternative is AIM-1 - maintain the platform in its as-is condition and inspect on a frequent basis. Again, the variation in C_D appears to have no effect on the conclusion. This example demonstrates the importance of the platform replacement assumption and how it can modify the lowest cost alternative.

A summary of the AIM cost evaluation for Platform A (Figure 3-24) compares the cases with and without platform replacement. Note that the initial costs are lower than the future costs for the replacement option which showed AIM-4, repair and raise the deck, as the best alternative. When the potential future costs are high, the best solution is one that ensures the highest degree of safety (180-year return period for repair and raise (AIM-4) the deck versus 42-year return period for as-is (AIM-1)).

For the non-replacement option, the initial costs are higher than the future costs. In this case, as shown by this example, the lowest initial cost (AIM-1) is preferred.

An alternative evaluation of the future costs could be based on the premises that the platform operator/owner has already included the costs of abandonment in an accrual fund, and that there will be additional costs associated with deferred production and well control in the event of failure (refer to G. C. Lee evaluation, Appendix E). The total future cost changes from \$30.2 M (Figure 3-20) to \$48.7 M (Appendix E). The relative ranking of the AIM alternatives due to this modification remains unchanged for the replacement and non-replacement options.

Another issue in an economic evaluation regards present valuing potential future costs [46]. One simple continuous discount model (presumes replacement of failed facilities) defines present value (PVF) future cost for a platform life L, investment rate, r, and inflation rate, q, as:

$$PVF = \frac{1-[1+(r-q)]^{-L}}{(r-q)}$$

For example, a net discount rate (r - q) of 15 percent for a life of 12 years would result in a PVF = 5.4. In the case of AIM Alternative 1 (Figure 3.21), the expected cost would be \$4.3 million [E(C) = 0.4 + (1/42) x 5.4 x 30.2 = \$4.3 m]. Again, each of the alternatives would be affected without changing their rank order.

Another evaluation could explicitly include considerations of uncertainties in initial and future costs. For example, the coefficient of variation (ratio of Standard Deviation, σ, to mean value) associated with the AIM-4 alternative initial costs (Figure 3-19) might be estimated as 30 percent, i.e.,

$$+1\ \sigma\ CI = 1.3 \times \$2.75\ M = \$3.5\ M$$

The Coefficient of Variation associated with the estimated future costs associated with replacement (Figure 3-20) might be estimated to be 80 percent, i.e.,

$$+\ 1\ \sigma\ CF = 1.8 \times \$30.2\ M = \$54.4\ M$$

The resultant Coefficient of Variation of the total expected cost of \$4.71 M would be approximately 85 percent, $(.3^2 + .8^2)^{1/2}$. This would indicate a $\pm 1\ \sigma$ total cost range of \$8.71 M to \$0.71 M. Again, the rank order of the AIM alternatives remains unchanged; however, the decision-maker now has an appreciation of the potential up-side and down-side economic implications of each alternative.

The last step in the commercial evaluation is to assure that the platform operations represent an attractive investment. The net value of the platform operation is about \$95 million (Appendix D). The expected total cost of the AIM program is about \$5 to \$6 million (AIM-4) with an initial cost of about \$3 million. Thus the AIM program to keep this platform in service represents an initial AIM investment of about 3 percent of the facility's net worth. This investment would seem to be justified [57,58].

It is re-emphasized that the principal focus of the AIM alternative cost-benefit evaluation is on the process used to make decisions, i.e., a structured framework in which costs, risks, and benefits can be rationally evaluated [1]. There are many different, viable, economic evaluations that can be made in this framework and only several have been illustrated here. The "best" evaluation is the one that "best" incorporates the concerns and judgments of the decision makers [59]. Performing systematic, parametric sensitivity analyses of the technical (demand, capacity, probability of failure) and evaluation (alternatives, initial and future costs/risks) factors to determine their influences on defining the "best" alternative is an essential part of the decision-making process.

3.5.2 Historical, Standard of Practice Evaluation

The second process for reaching decisions/judgments concerning the suitability of a particular AIM program has been defined [1] as an historical, standard of practice (calibration) evaluation. This process is particularly attractive in public and regulatory evaluations/justifications in which industrial-commercial cost-benefit valuations (trade-offs) are implicit.

The basic premise of this process is that through experience, engineers, constructors, and operators (the "profession") have developed consensus guidelines and standards of practice that represent professionally acceptable solutions, recognizing industrial, regulatory, and general public interests and objectives.

An example of this premise is illustrated in Figure 3-25 [49]. This illustration summarizes the historical statistics on failures of major drilling and production platforms in the Gulf of Mexico. The statistics [50] are based on failures that involved hurricane wind, wave, and current loadings, and that resulted in total collapse of the structures or damage that was so extensive that the structures had to be salvaged (rendered unserviceable). Well jackets, caissons, and other similar "secondary" drilling-production structures are not included in these failure statistics. Note that following the mid-1950's (after Hurricane Hilda), the aggregated structure performance in the Gulf of Mexico has reached a failure rate of less than 0.3 percent per year. Experience through 1987 would indicate an average failure rate approaching 0.1 percent per year.

It is important to recognize that the Gulf's historical failure rate (for storm-induced events on major drilling and production platforms) involves structures installed since the 1950's. There is an extremely wide diversity in design criteria, construction, and operation maintenance practices in this population of structures. Also, it is important to note that the incidence of intense Gulf of Mexico hurricanes has been high (≥one storm per year) during this period, providing repeated tests of the performance of this population of structures.

With this background, one might justify the acceptability of an AIM program for a drilling and production platform based on its calculated (notional) failure rate (probability of failure). If the AIM program resulted in a failure rate of less than the historical 0.1 to 0.3 percent per year, then it could be acceptable.

As discussed in the AIM-I report [1] and reference [51] (Appendix F), there are three key problems with this approach. The first regards potential deficiencies in the historical data base on platform failures.

The second regards potential deficiencies in the calculated failure rates. The third regards the implicit nature of the consequences associated with the historical failures and the changing industrial-regulatory-public reactions to these consequences.

Basically, little can be done to improve/enhance the historical data base, so the first potential deficiency must remain inherent to this approach.

Relative to the comparison of historical/actuarial failure rates with calculated/notional failure rates, one must first recognize some important differences between the two [Appendix E]. The first regards the mixtures of inherent, modeling, and systematic uncertainties or variabilities in the computed rates. In the "real" actuarial case, many of these uncertainties are not operative. The hurricane exerts a certain maximum lateral force/demand on the structure. The platform has a certain capacity to resist this demand. We just don't know precisely what these demands and capacities are. If we introduce uncertainties that are not present in the real situations ("test"), then we will tend to over-estimate the true or actuarial failure rates. It is for this reason, among others (e.g., simplicity) that the AIM-I applications have involved a single source of uncertainty or variability in determining the projected failure rates; that associated with the loading (force effect) or demand(s) developed by environmental "events" (intense hurricanes, earthquakes, ice, mudslide and other ocean hazard loading/demand scenarios).

Note that the simple approximations of the failure rate ($P_{fa} = 1/RP_{ULS}$) can "work" for several reasons. First, because of the very large uncertainties of the environmental loading (force effect) demands relative to those of the platform capacities. Generally, the environmental demands (forces) have variabilities that are factors of 2 to 10 times those of the platform capacities [44]. At the lower end of this range (2-3), the computed failure rates may be too low; however, for the remaining range, the approximation provides a reasonable approximation of "reality" (observed failure rates). If the variabilities of the demands approach those of the capacities, then more "precise" methods should be used to compute the platform system failure rates [52].

A second reason that the approximation can work is that it tends to include only those natural/inherent (Class I) variabilities associated with the predominant or demand hazard (e.g., the expected maximum hurricane force effect on a given platform at a given location). The expected (or best estimate) failure rate is based on the best estimate Ultimate Limit State (ULS) capacity of the structure. Potential ranges on the best estimate failure rate are based on potential ranges in the ULS capacities of the platform (recognizing defect, damage, time-fatigue, and repair-maintenance effects), and on potential ranges in the maximum demands (recognizing uncertainties associated with our professional/analytical limitations in defining the loads and/or force effects). In this way, the professional analytical uncertainties (Class II) are kept explicit in the process of evaluating parametric sensitivities of the best AIM alternative.

It should also be noted that the use of the computed failure rate in the commercial cost-benefit evaluation discussed in the preceding section can have validity in that it is used in a comparative sense (one alternative versus another). It is used as a "weighting" function or index to merge "certain" (highly likely) initial AIM costs with "uncertain" (highly unlikely) future AIM costs [1].

Continuing with the historical, standard of practice evaluation, an extension of the information contained in the Gulf of Mexico platforms failure rate (Figure 3-24) has been provided by Whitman [53] (Figure 3-26). This information addresses offshore fixed and mobile drilling platforms in the context of world-wide experience and in reference to other engineered structures (industrial and public sectors). Most importantly, the ranges of consequences associated with the ranges of failure rates are identified (including potential economics ranges and injury ranges).

This information provides a potentially strong basis on which to judge "suitability for service," given a particular AIM program/strategy. The region that divides acceptable from unacceptable risks and consequences (lines labeled "acceptable" and "marginally acceptable") represent the investigators' evaluation of what society has determined as an equitable or reasonable trade-off of costs and risks. The "acceptable" risk rate (annual, $P_{fa/A}$) is related to the economic/cost consequences (CT) as follows:

$$P_{fa/A} \cong 10^{-(0.75 \log CT + 1.75)} \qquad \text{Eq. (3-1)}$$

where $P_{fa/A}$ is the failure rate per year and CT is the total cost associated with the failure (in millions of 1984 dollars, \$M).

The "marginally acceptable" risk rate ($P_{fa/M}$) is related to CT as follows:

$$P_{fa/M} = 10^{-(0.675 \log CT + 0.975)} \qquad \text{Eq. (3-2)}$$

Note that the number of potential injuries to personnel associated with an economic loss of serviceability is about $1 M per injury. Thus, if personnel injuries need to be evaluated, they can either be integrated with the other cost consequences or evaluated separately. In the latter case, the CT is replaced with the expected <u>number</u> of injuries to determine the target risk ranges. Note that the expected number of injuries should recognize the effects of injury prevention measures taken on the platform (another set of AIM alternatives in the case of manned platforms). In the cases of Platforms A and B, they are not continually manned, and personnel injuries are not an issue.

Continuing with the Platform A example, the most attractive AIM alternative in the case of replacement of the platform in the event of loss of serviceability based on the cost-benefit evaluation was to maintain the platform in its present conditions (AIM-4, Figure 3-24). In this condition, the failure rate was estimated as 0.56 percent per year (180-year RP) and the loss of serviceability consequences estimated as $30.2 M (Figure 3-20). The failure rate for this scenario would be too high if the historical Gulf of Mexico platform failure rate valuation (P_f = .1 - .3%, Figure 3-25) were used.

The more comprehensive valuation involving both risks and consequences (Figure 3-26) would indicate:

$$F_{fa/A} \cong 0.14 \quad percent$$

and

$$F_{fa/M} \cong 1.1 \quad percent$$

Thus, this alternative (P_f = 0.56%) would fall into the range of the risk-consequence based valuations.

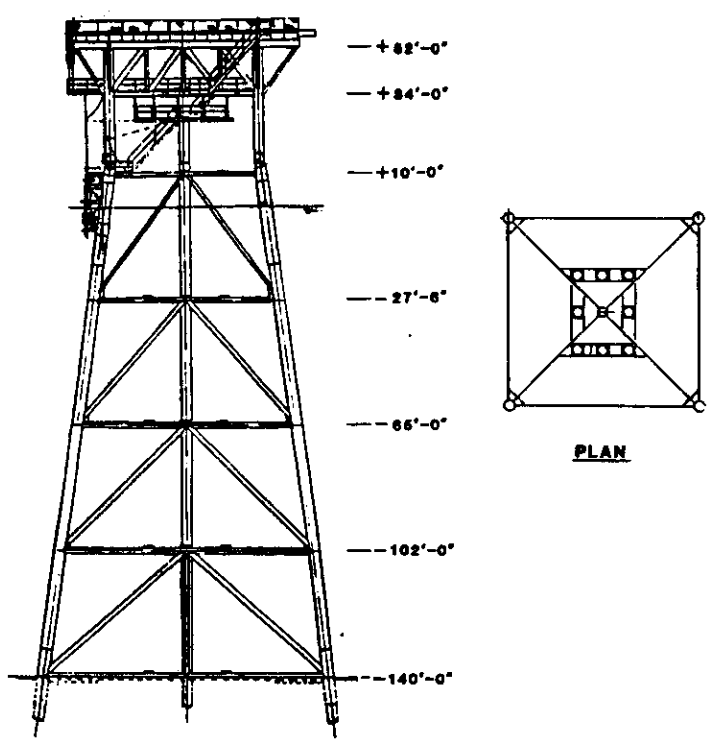
In the case of the non-replacement scenario, the most attractive alternative (AIM-4, Figure 3-24) would result in a computed failure rate of 2.3 percent per year (42-year RP) with a total consequences cost of $3.3 M. This alternative would fail to satisfy the historical Gulf of Mexico platform failure rate (Figure 3-25), but it would qualify when the risk-consequences were evaluated (P_f = 0.73 to 4.7%).

Note that if the basis for justification of acceptability were taken as that implied in current practice for Gulf of Mexico platforms, failure rates in the range of 10^{-3} to 10^{-4} could be implied [44,52,55]. It should be obvious that this would not be a reasonable basis on which to determine or justify acceptability.

Similar comments can be made with respect to basing the determination of acceptability on returning the structure to its original strength/capacity (1060 kips). At this capacity,the platform has a computed failure rate of approximately 2 percent per year, clearly in excess of recent (post-1950's) acceptable rates (Figure 3-25).

Given a justifiable, standard of practice-based definition of an "acceptable" and "marginally acceptable" combination of risk rate and consequences (e.g., Figure 3-25, Eqs. 3-1 and 3-2), a regulator/operator could determine if the structure and its proposed AIM program meets the defined guidelines for the required standard of practice in requalifying platforms. At this point, the regulator could be assured that the platform did or did not meet the guidelines. If the platform could be brought to the standard of practice guidelines using a particular AIM program, then the regulatory justification could be facilitated. It would then be up to the platform operator to demonstrate to his company that the platform operations, its AIM program, and its income producing potential were a justifiable business venture.

- Installed 1963
- 140-ft Water Depth
- 5 Legs (39" Diameter, 0.5")
- 9 Wells (Well in Center Leg)
- K-Braced (14" to 20" Diameter, 0.375")
- Damaged Braces (Some Repaired)
- 36" Diameter Piles (4) + 30" Diameter Center Conductor/Pile - (Shimmed)
- 10-ft Thick Layer of Soft Clay Overlies Firm to Stiff Clays
- Lower Equipment Deck at +34 Ft
- Gas Production
- Unmanned
- 12-Year Remaining Economic Life



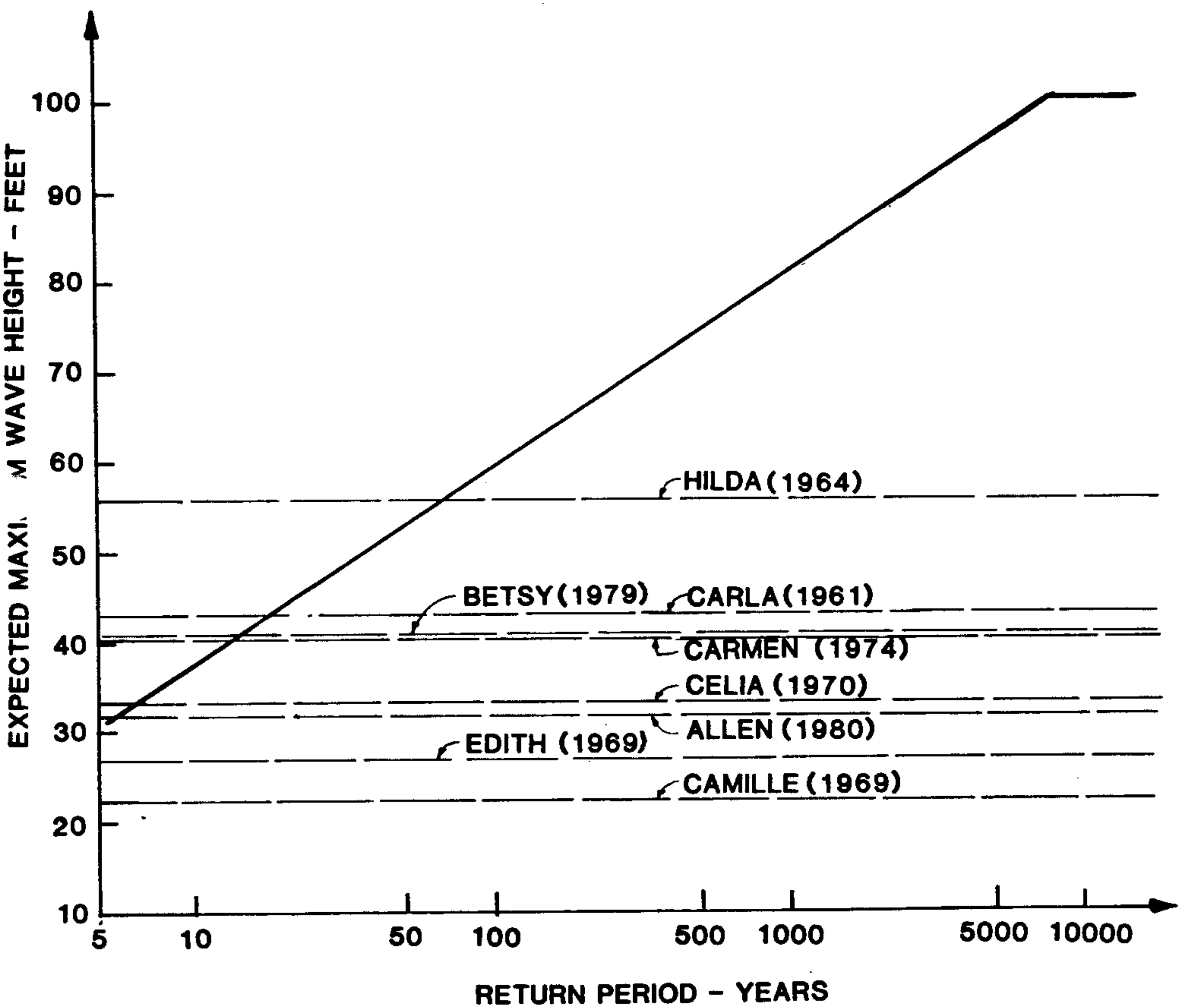
PLATFORM "A" DESCRIPTION

FIGURE 3-1

ITEM NO.	LOCATION	DAMAGE
1	Vertical Interior Diagonal B2 at -27.5′ to Center Leg at -65′	Missing
2	Vertical Interior Diagonal B1 at -27.5′ to Center Leg at -65′	Completely Separated from Leg at B1
3	Vertical Face Diagonal, Row B Midpoint B1 to B2 at -27.5′ to B1 at -65′	Completely Separated from Horizontal Member B1 to B2 at -27.5′
4	Vertical Face Diagonal, Row B Midpoint B1 to B2 at -65′ to B1 at -102.5′	Completely Separated from Horizontal Member B1 to B2 at -65′
5	Vertical Interior Diagonal A2 at -27.5′ to Center Leg at -65′	Cracked at A2 from 12:00 to 5:00 Crack Length = 40"
6	Horizontal Interior Diagonal -65′ B2 to Center Leg	Cracked at B2 from 9:30 to 2:30 Crack Length = 14"
7	Horizontal Interior Diagonal -28′ B2 to Center Leg	Cracked at B2 from 4:00 to 8:30 Crack Length = 12.75"
8	Horizontal Interior Diagonal -28" A2 to Center Leg	Cracked at A2 at 4:30 Crack Length = 12.5"
9	Horizontal Face Member Row B B1 to B2 at -65′	Cracked at B2 at 3:00, 5:00, 9:00 Crack Length = 7.25" Total

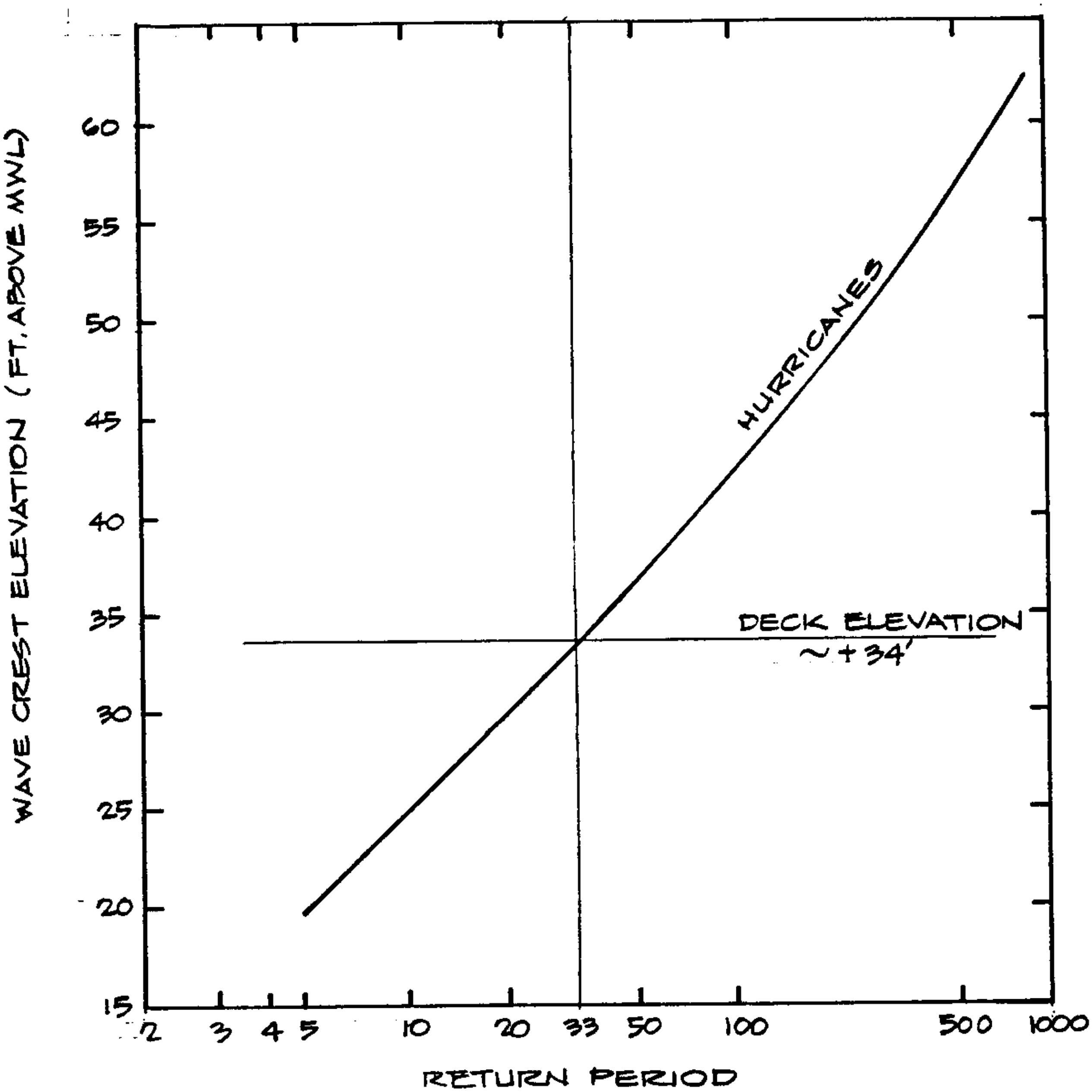
PLATFORM "A" DAMAGE REPORT SUMMARY

FIGURE 3-2



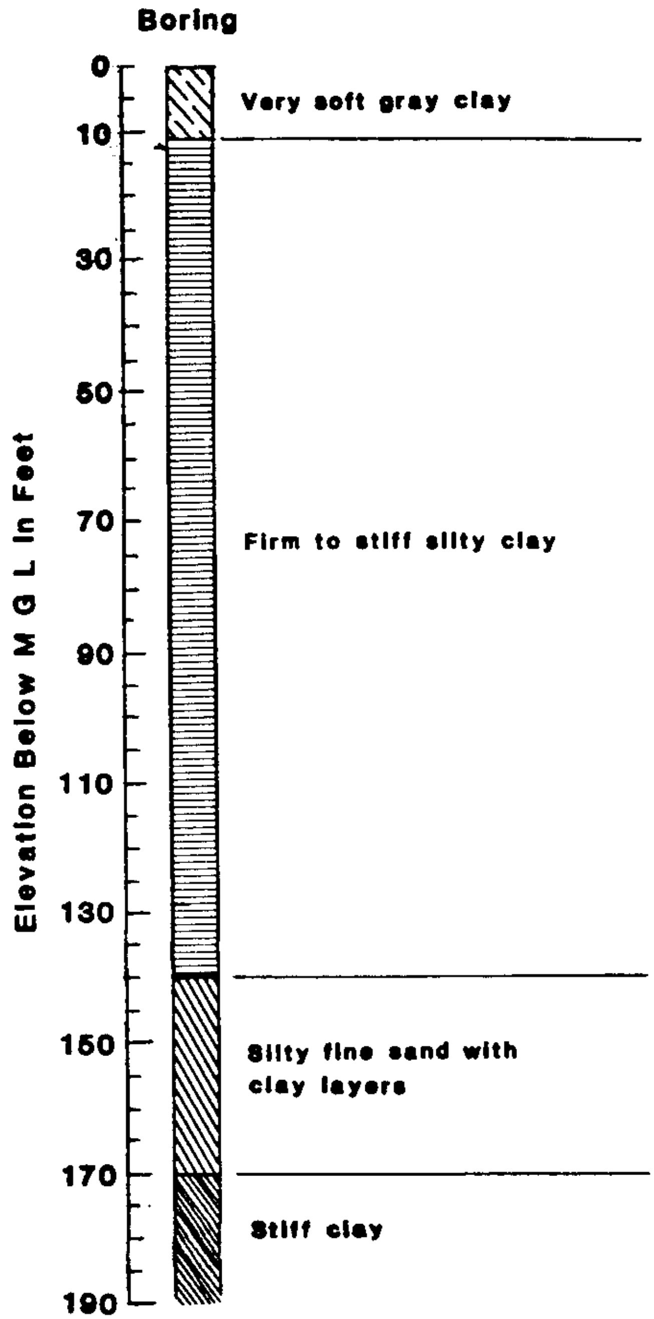
WAVE HEIGHT VS. RETURN PERIOD - PLATFORM "A"

FIGURE 3-3



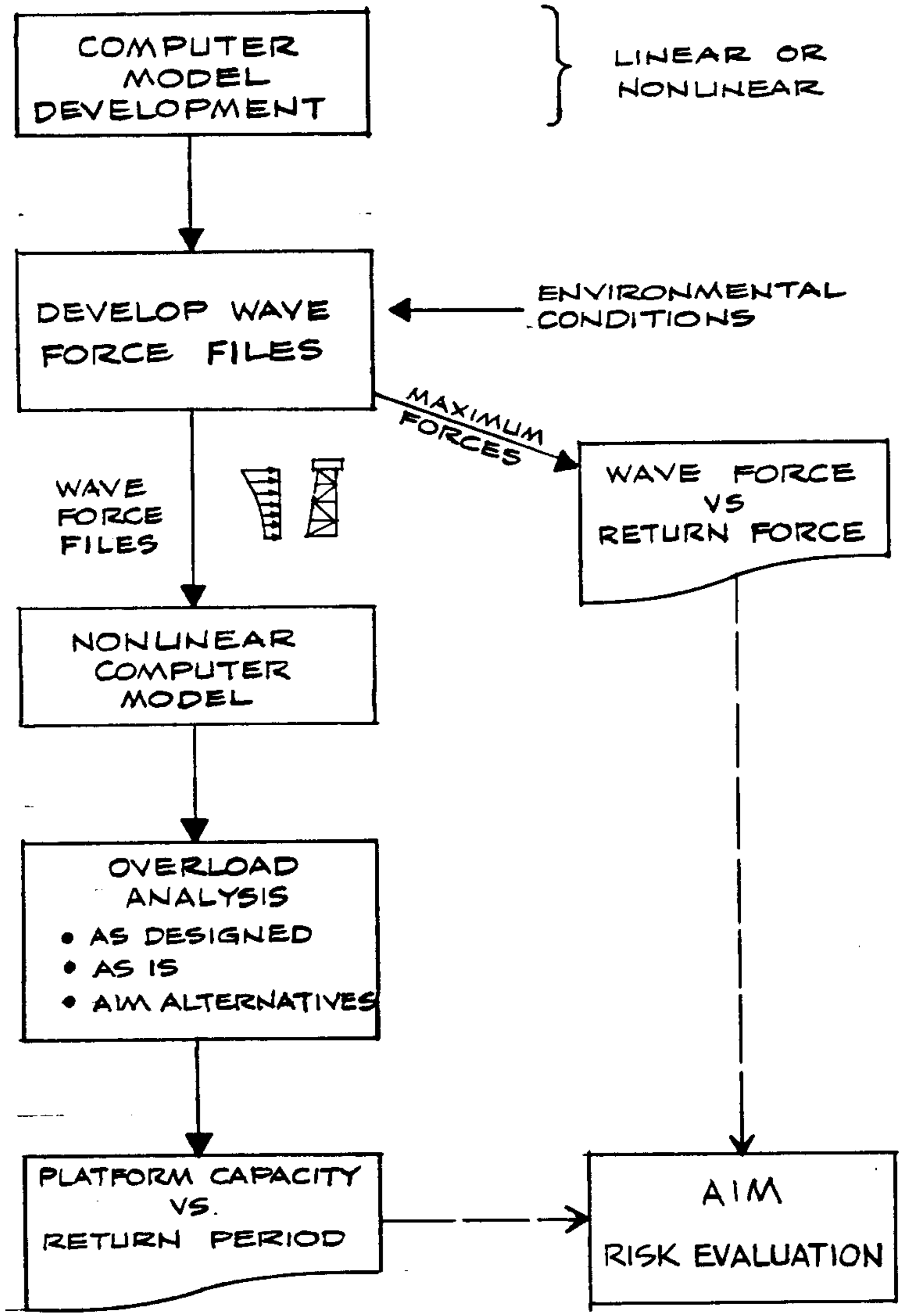
WAVE CREST ELEVATION - PLATFORM "A"

FIGURE 3-4



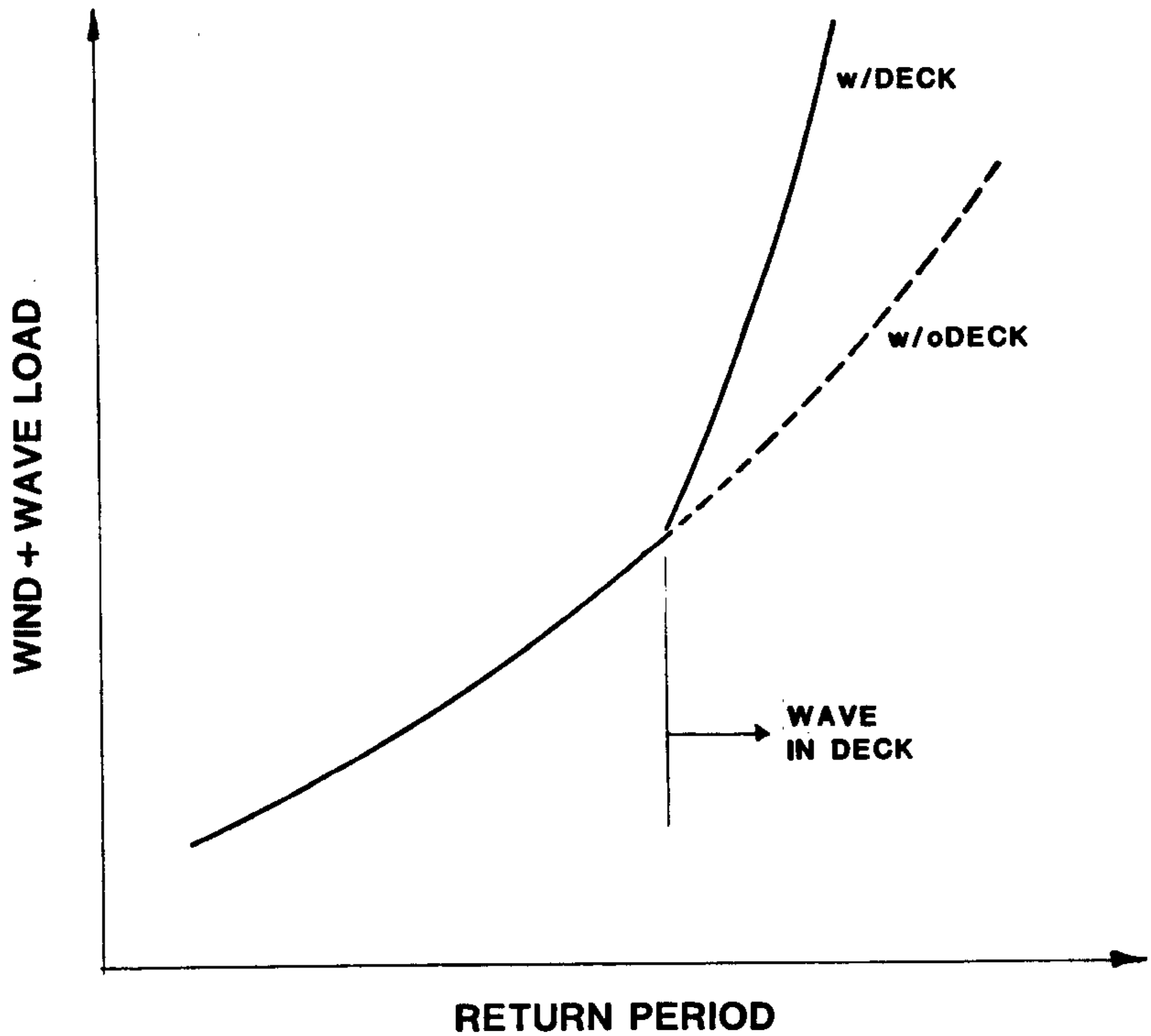
SOIL CONDITIONS - PLATFORM "A"

FIGURE 3-5



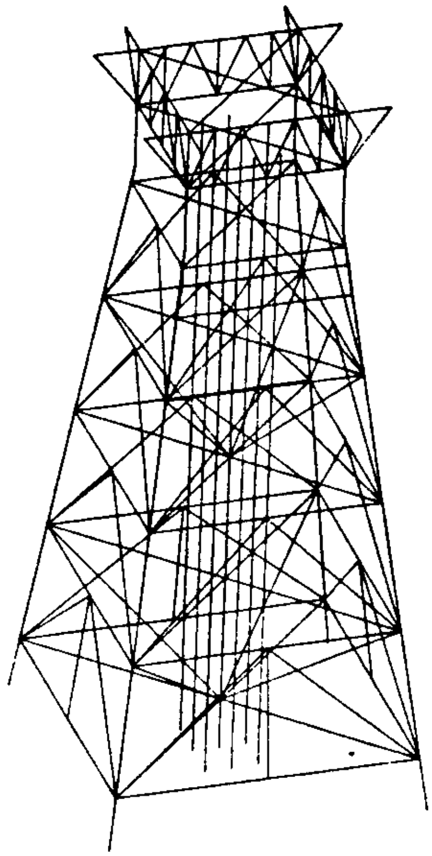
AIM FORCE/CAPACITY EVALUATION

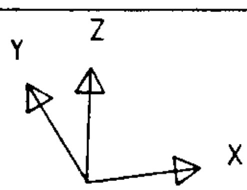
FIGURE 3-6



ENVIRONMENTAL LOADING RELATIONSHIP

FIGURE 3-7





GLOBAL AXES

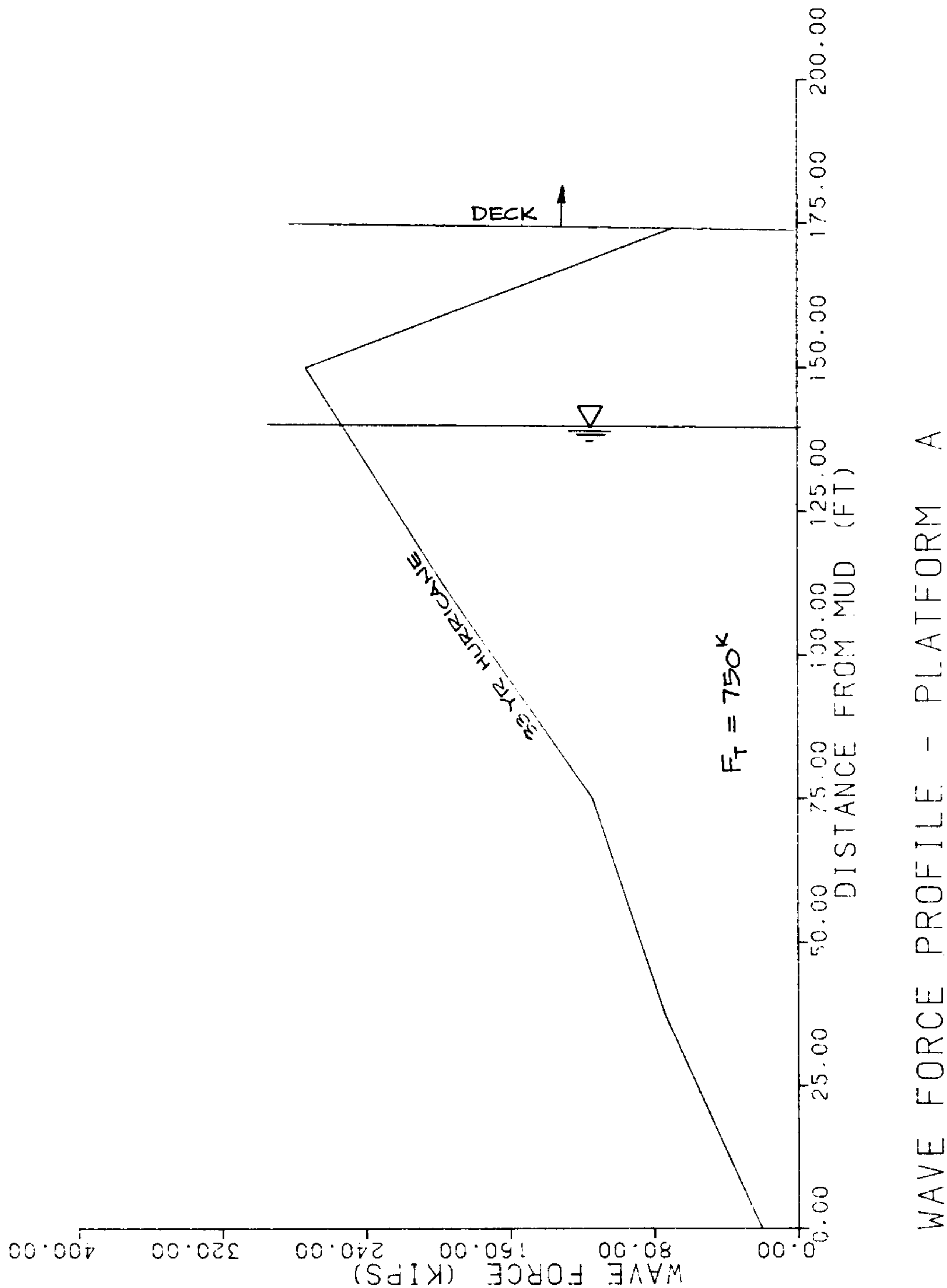
3-D COMPUTER MODEL - PLATFORM "A"

FIGURE 3-8

SEARISER Version 2.0

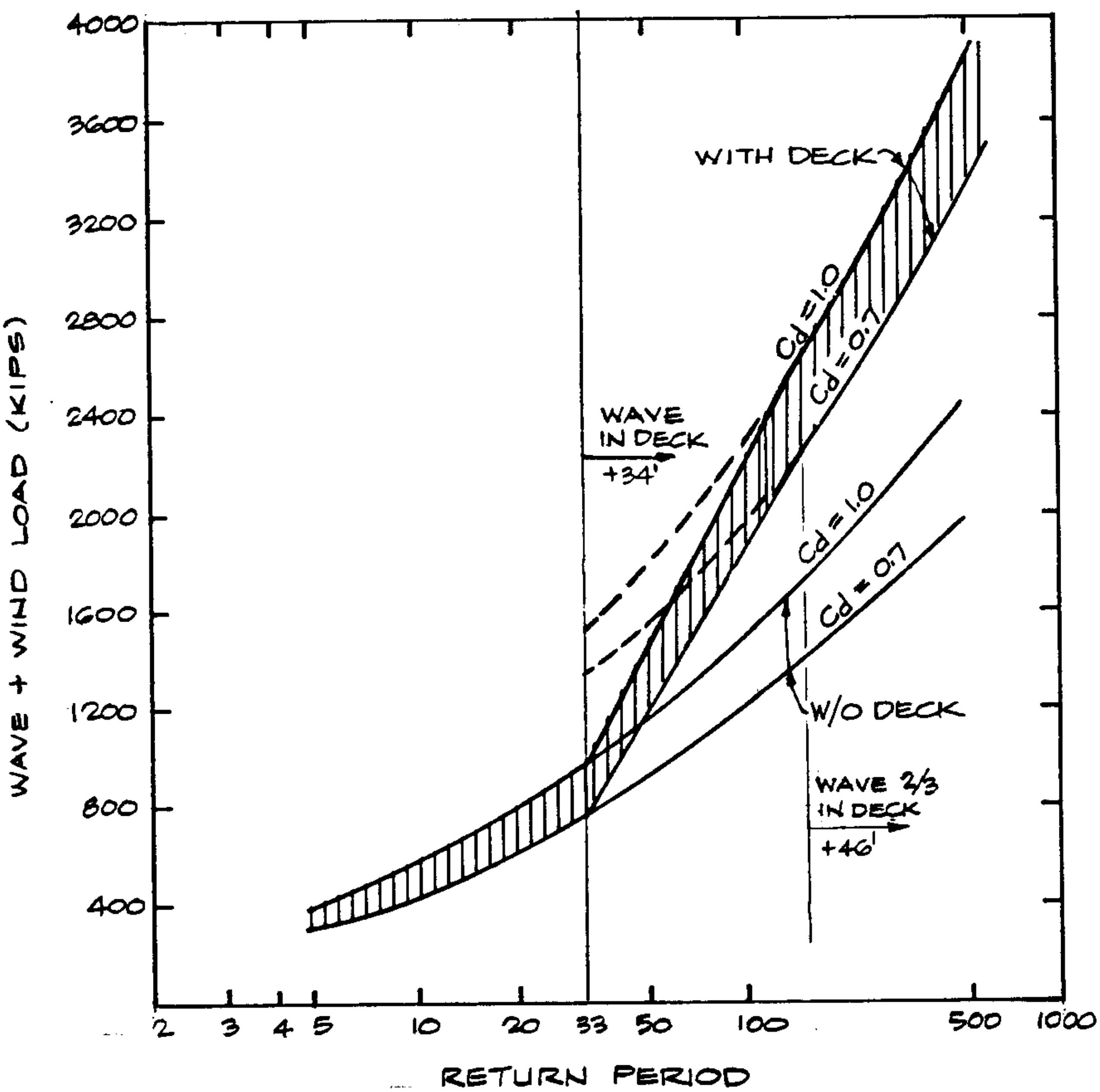
DATE - 87/06/05

TIME - 18:03:37



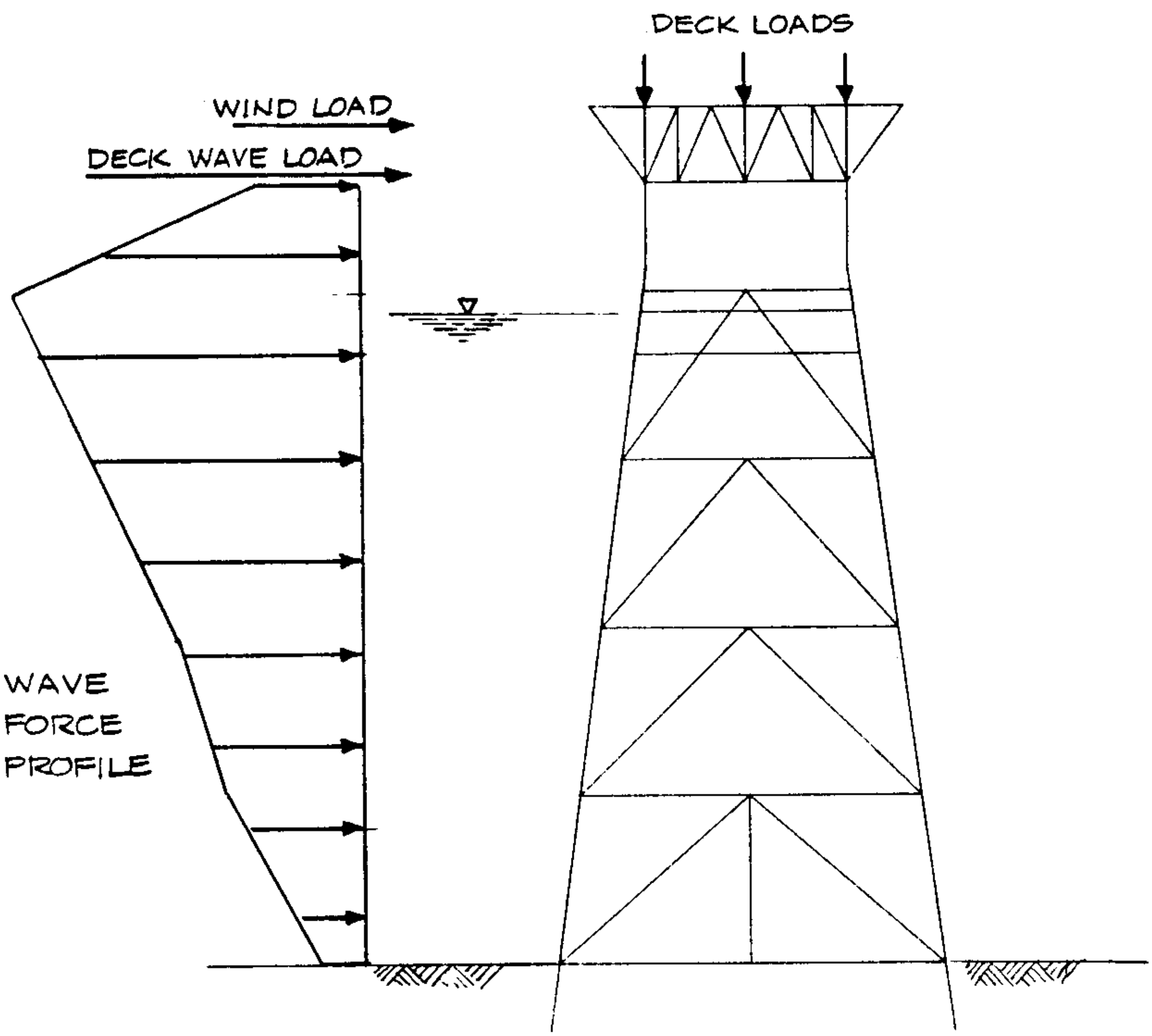
WAVE FORCE PROFILE - PLATFORM "A"

FIGURE 3-9



ENVIRONMENTAL FORCE VS. RETURN PERIOD - PLATFORM "A"

FIGURE 3-10



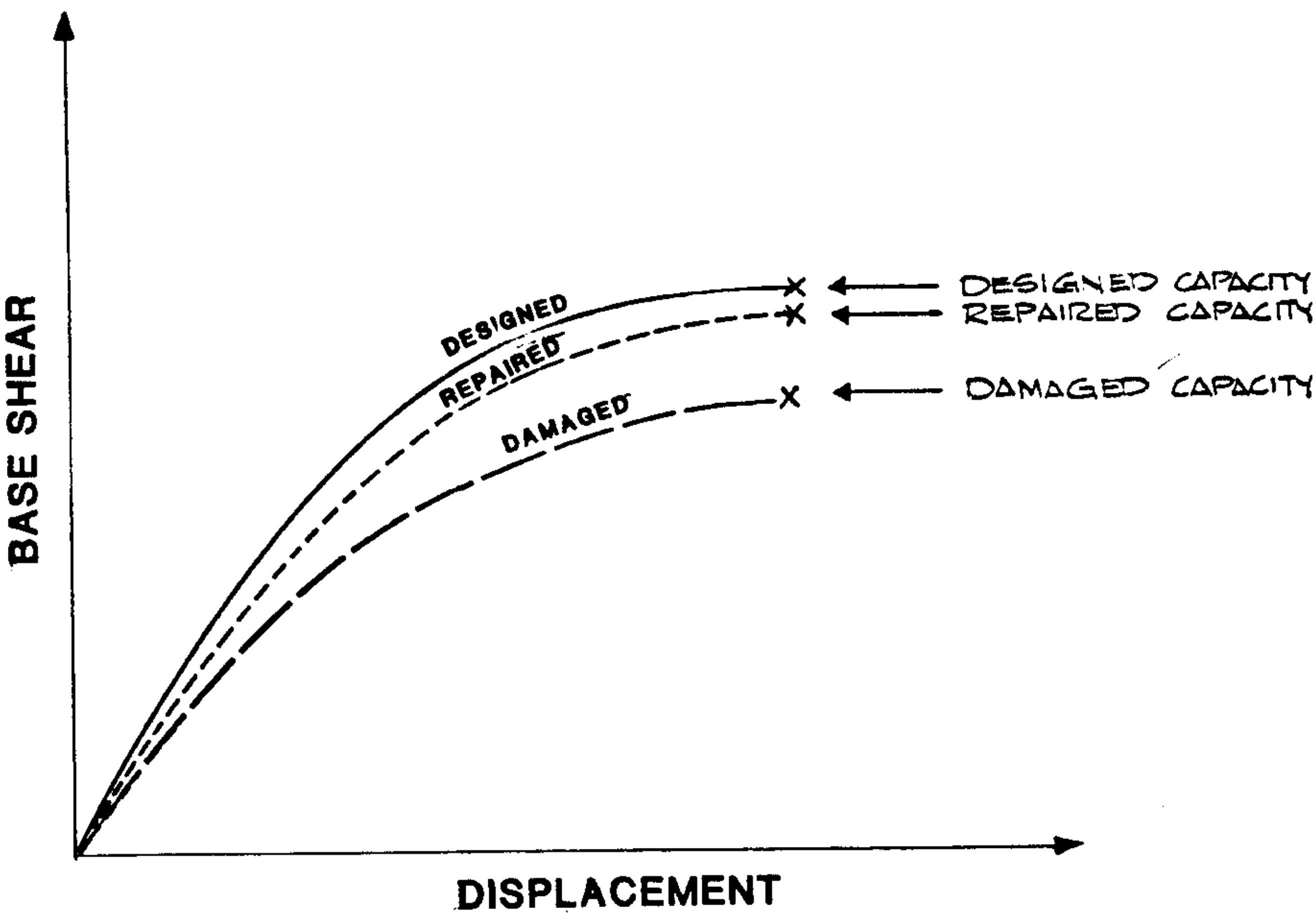
LOAD SEGMENT 1 = DECK LOADS

LOAD SEGMENT 2 = WAVE PROFILE + WIND (WAVE BELOW DECK)

LOAD SEGMENT 3 = DECK WAVE (WAVE IN DECK)

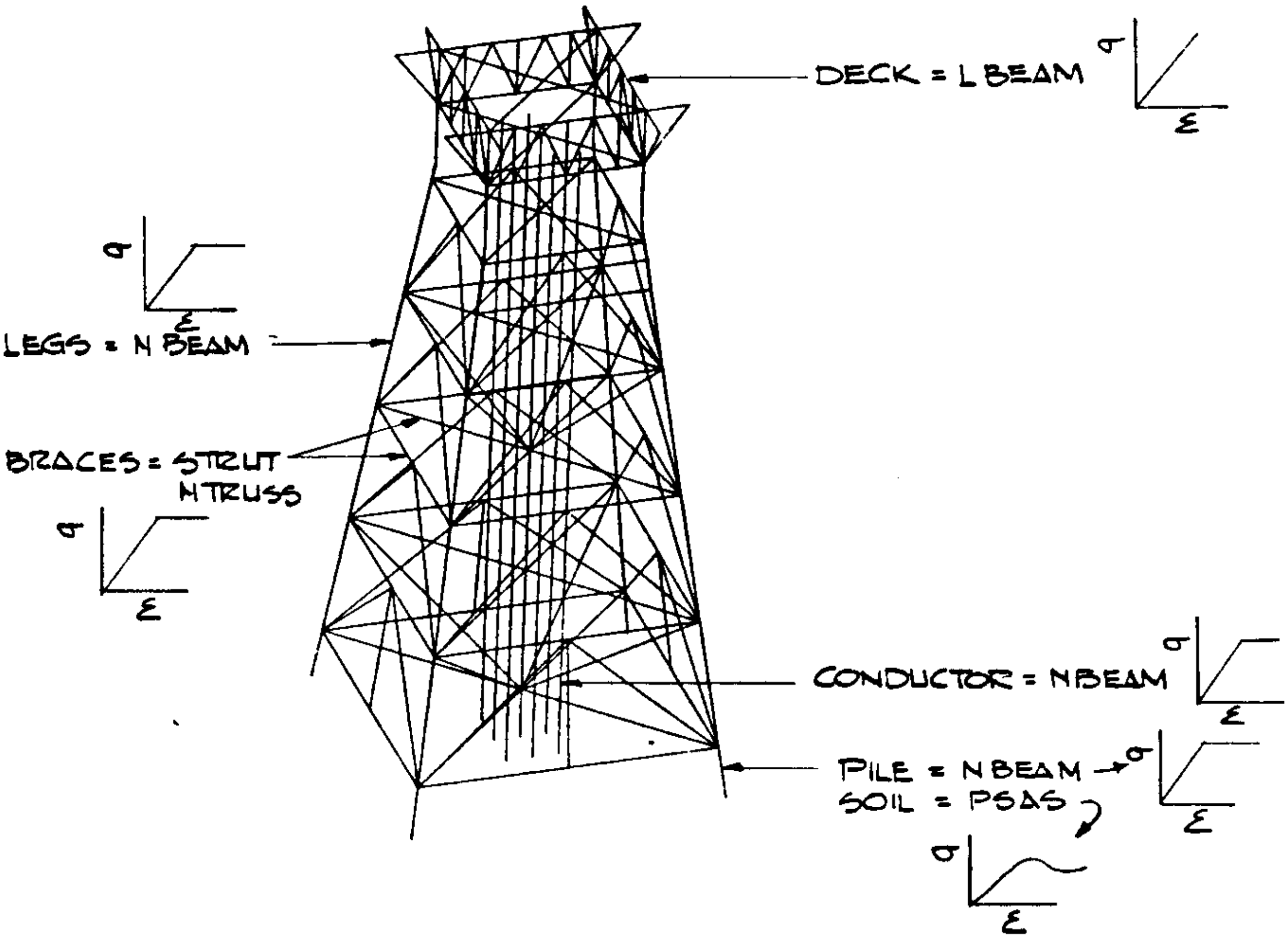
AIM OVERLOAD CONDITIONS

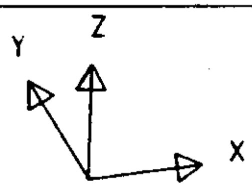
FIGURE 3-11



PLATFORM PERFORMANCE RELATIONSHIP

FIGURE 3-12





GLOBAL AXES

NONLINEAR COMPUTER MODEL - PLATFORM "A"

FIGURE 3-13

SEARISER Version 2.0

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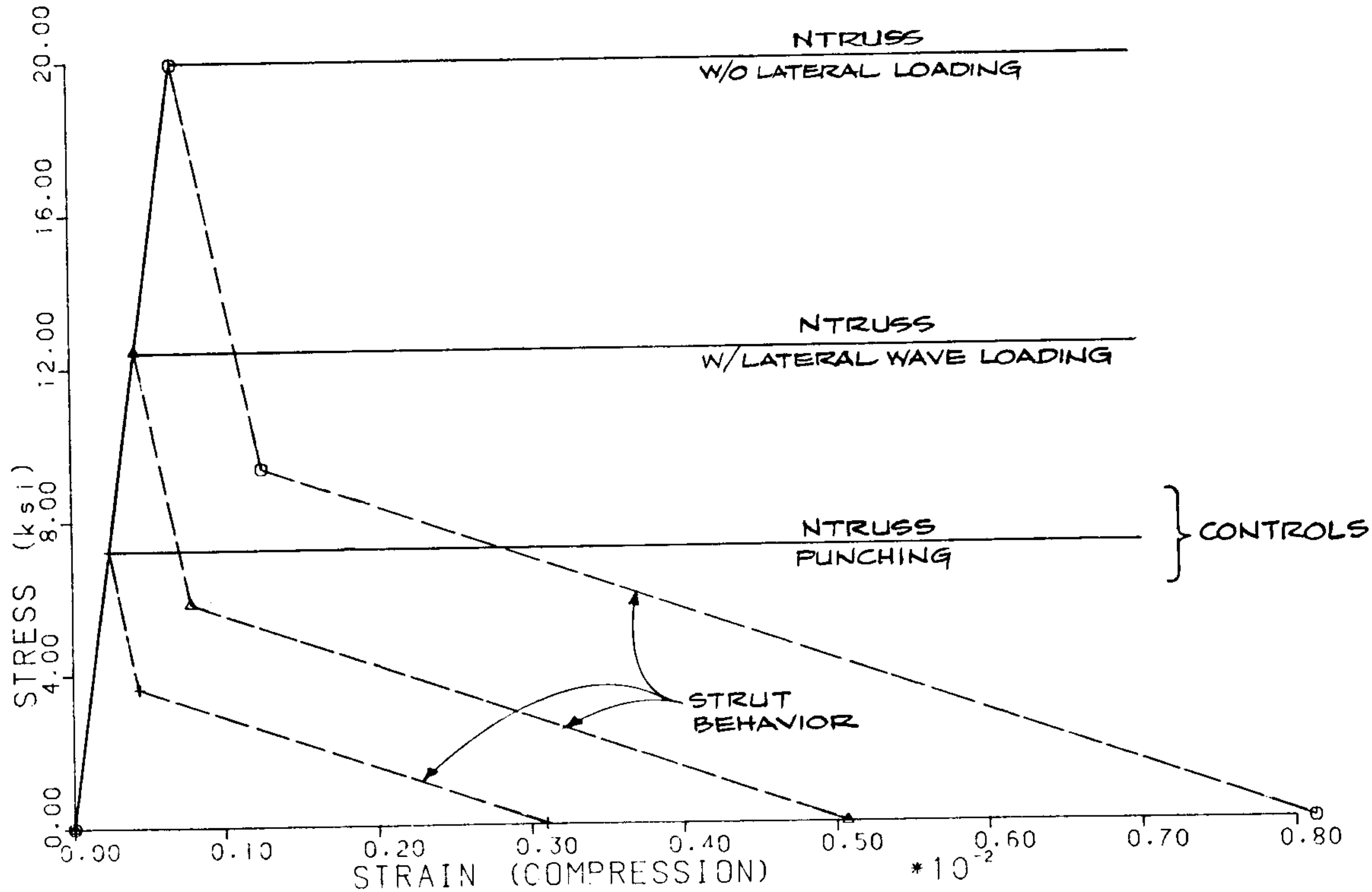
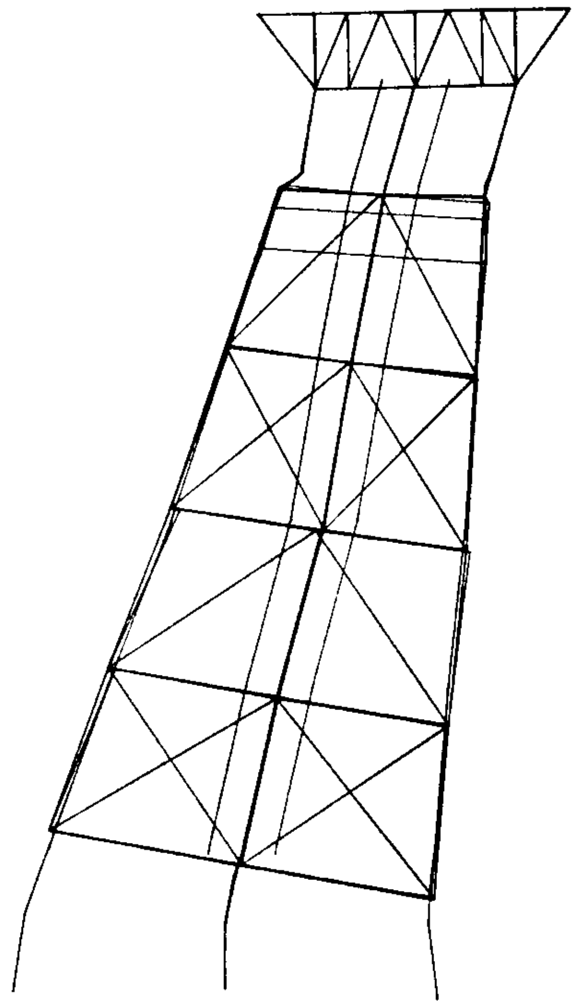
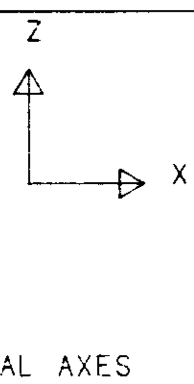


MATERIAL CURVE FOR BRACES

FIGURE 3-14

PMB Systems Engineering Inc. San Francisco, Calif. 94111





DEFORMED SHAPE - PLATFORM "A"

FIGURE 3-15

SEARISER Version 2.0

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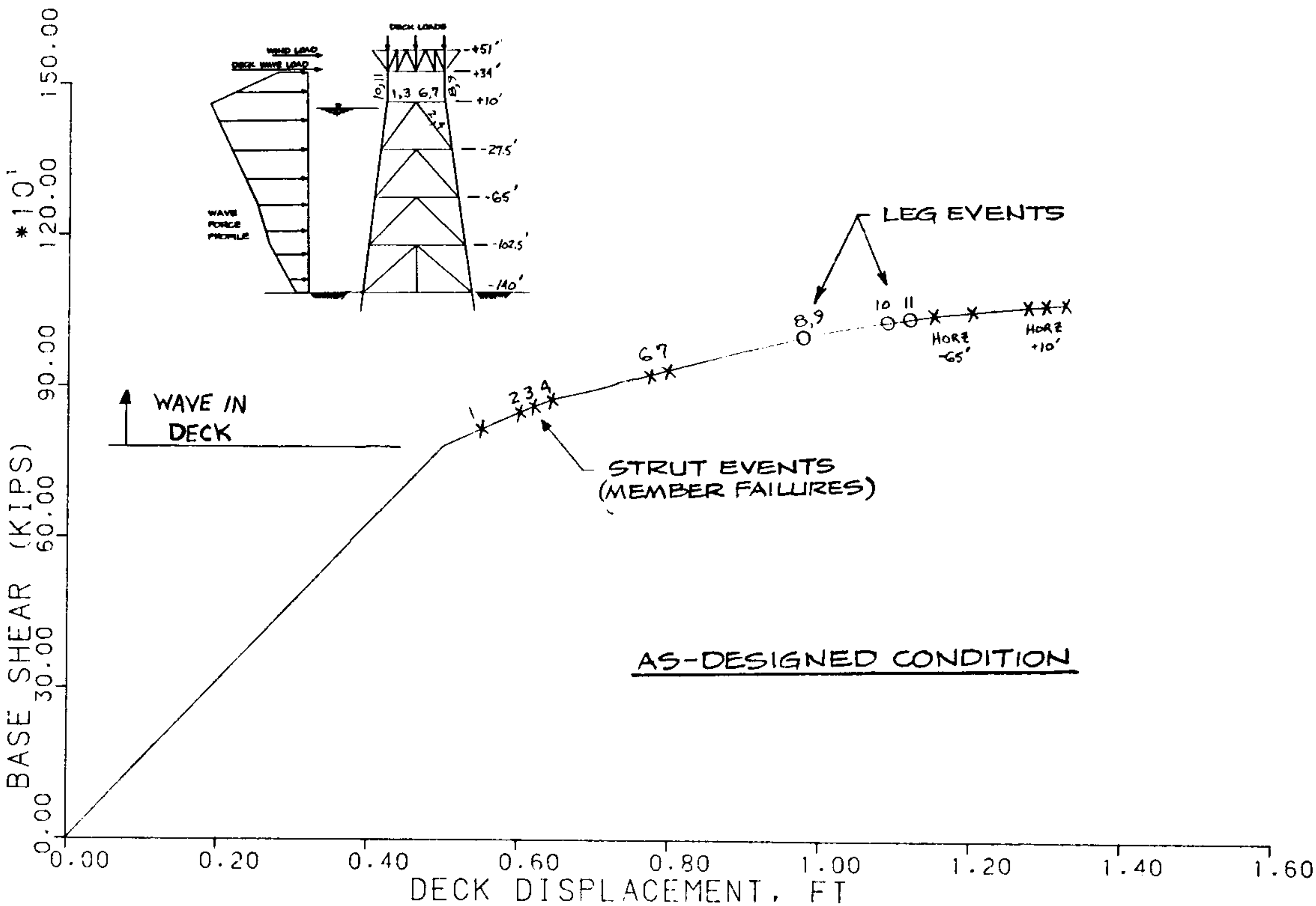
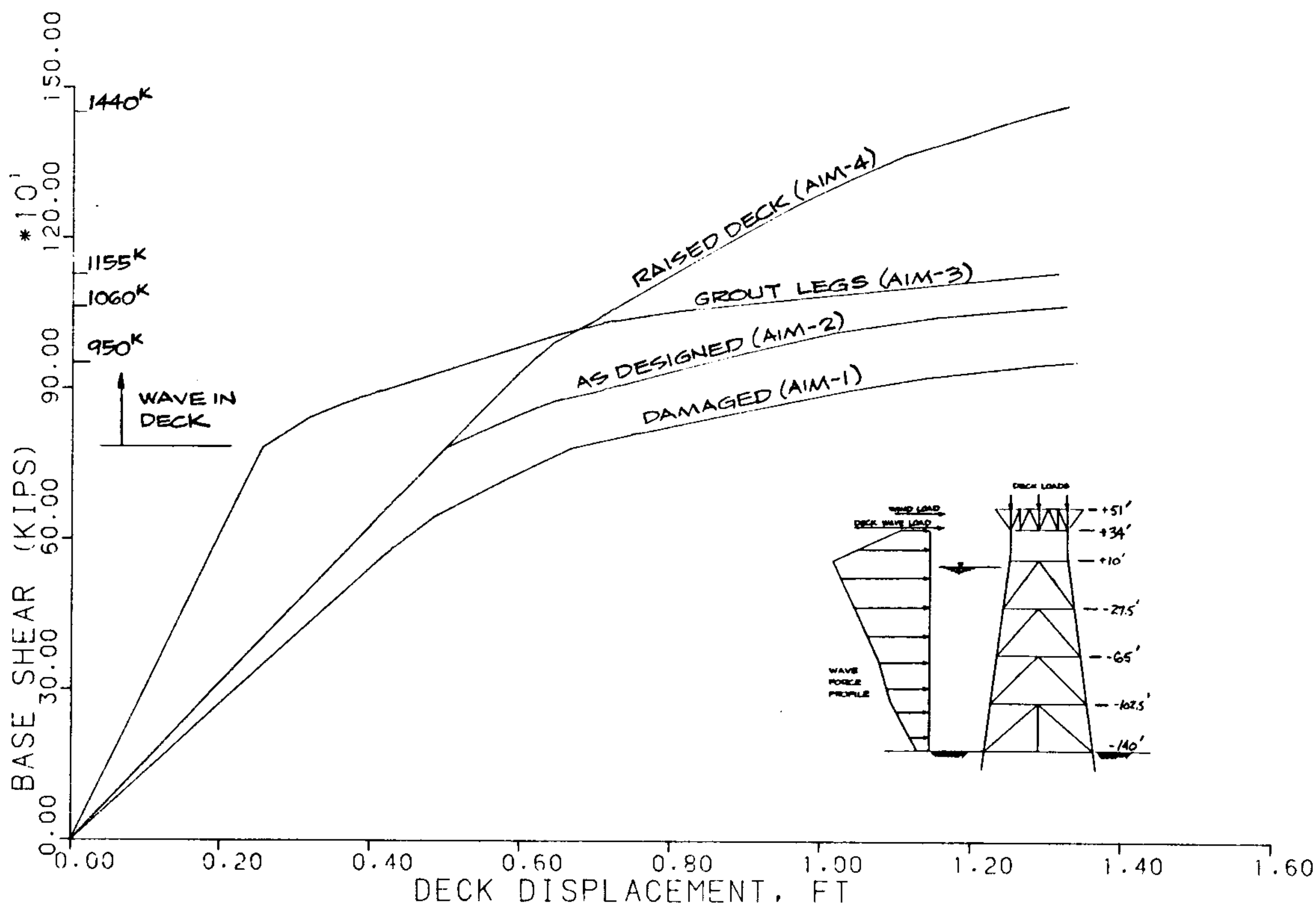
TIME - 09:24:10



LOAD DISPLACEMENT CURVE - PLATFORM "A"

FIGURE 3-16



LOAD DISPLACEMENT CURVES - AIM ALTERNATIVES - PLATFORM "A"

FIGURE 3-17

A. STRUCTURE REPAIRS AND MODIFICATIONS	
- All Repairs	$1,300,000
- Grout Legs	$ 50,000
- Raise Deck	$1,000,000
B. OPERATIONS (REMOVE EQUIPMENT, ETC.)	None
C. ENGINEERING (AIM AND MISCELLANEOUS	$ 100,000
D. INSPECTIONS	
- Extensive (Single Platform Exhibits Damage History)	$ 50,000 per Inspection
- 2-Year Intervals (6 to Life)	$ 300,000

INITIAL AIM COSTS - PLATFORM "A"

FIGURE 3-18

AIM Alternative 1	Cost
Make No Repairs	$0.0 M
2-Year Inspections (Extensive)	$ .3 M
Engineering	$ .1 M
	$ .4 M Total Cost

AIM Alternative 2	Cost
Repair All Elements	$1.3 M
2-Year Inspections (Extensive)	$ .3 M
Engineering	$ .1 M
	$1.7 M Total Cost

AIM Alternative 3	Cost
Repair All Elements	$1.3 M
Grout Legs	$ .05 M
2-Year Inspections (Extensive)	$ .3 M
Engineering	$ .1 M
	$1.75 M Total Cost

AIM Alternative 4	Cost
Repair All Elements	$1.3 M
Raise Deck 13′ (180 Yr. RP)	$1.0 M
2-Year Inspections (Extensive)	$ .3 M
Engineering	$ .1 M
	$2.7 M Total Cost

PROJECTED INITIAL COST OF AIM ALTERNATIVES - PLATFORM "A"

FIGURE 3-19

A. NET REVENUES

Equilibrate with Time

Net Cost =	$ 0.0

B. RESTORATION COSTS

Salvage	$ 1,000,000	
Plug and Abandon 9 Wells	500,000	(Mob/demob)
	1,800,000	P & A - 9 x $200,000/ea
TOTAL COST	$ 3,300,000	

C. REPLACEMENT COSTS

Jacket	400 T @ 1250	$ 500,000
Deck	400 T @ 1750	$ 700,000
Piling	575 T @ 750	$ 431,000
Equip	(w/o Quotes)	$ 1,825,000
Install	11 days @ 50,000	$ 550,000
Contingency	10 percent	$ 400,000
		$ 4,400,000
Redrill Wells	2.5M/ea x 9	$22,500,000
TOTAL COST		$26,900,000
TOTAL FUTURE COST		**$30,200,00**

PROJECTED FUTURE COSTS - PLATFORM "A"

FIGURE 3-20

$$E(C) = E(I) + E(F)$$

Conditions:

- 12-Year Remaining Life
- Platform Replacement
- $C_D = 0.7$

Alternative 1: As-Is (AIM 1)			
E(I):	.40 M		
E(F):	- Platform Capacity (Damaged Curve)	=	950 k
	- Return Period	=	42 Years
	- Cost = 3.3 + 26.9	=	30.2 M
E(C) =	.40 + (1/42) x 30.2 x 12		
E(C) =	.40 + 8.63	=	9.03 M

Alternative 2: Repair (AIM 2)			
E(I):	1.7 M		
E(F):	- Platform Capacity (Repaired Curve)	=	1060 k
	- Return Period	=	45 Years
	- Cost	=	30.2 M
E(C) =	1.7 + (1/45) x 30.2 x 12		
E(C) =	1.7 + 8.05	=	9.75 M

AIM COST CALCULATIONS - PLATFORM "A"

FIGURE 3-21

$$E(C) = E(I) + E(F)$$

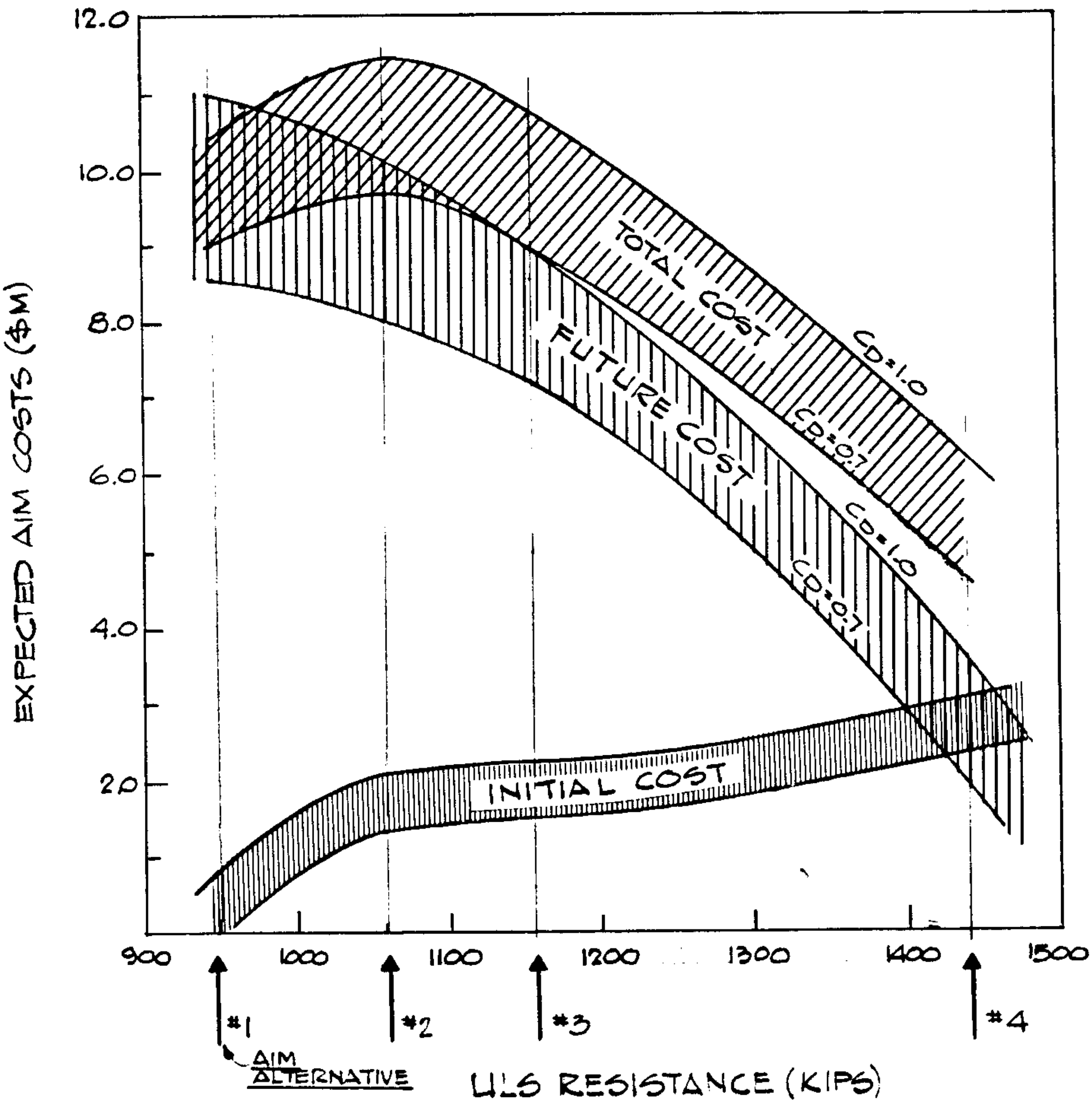
Alternative 3: Repair and Grout (AIM 3)			
E(I):	1.75M		
E(F):	- Platform Capacity (Repair and Grout Curve)	=	1155 k
	- Return Period	=	50 Years
	- Cost	=	30.2 M
E(C) =	1.75 + (1/50) x 30.2 x 12		
E(C) =	1.75+ 7.25	=	9.00 M

Alternative 4: Repair and Raise Deck (AIM 4)			
E(I):	2.70 M		
E(F):	- Platform Capacity (Raise Deck Curve)	=	1440 k
	- Return Period	=	180 Years
	- Cost	=	30.2 M
E(C) =	2.7 + (1/180) x 30.2 x 12		
E(C) =	2.70 + 2.01	=	4.71 M

AIM COST CALCULATIONS - PLATFORM "A"

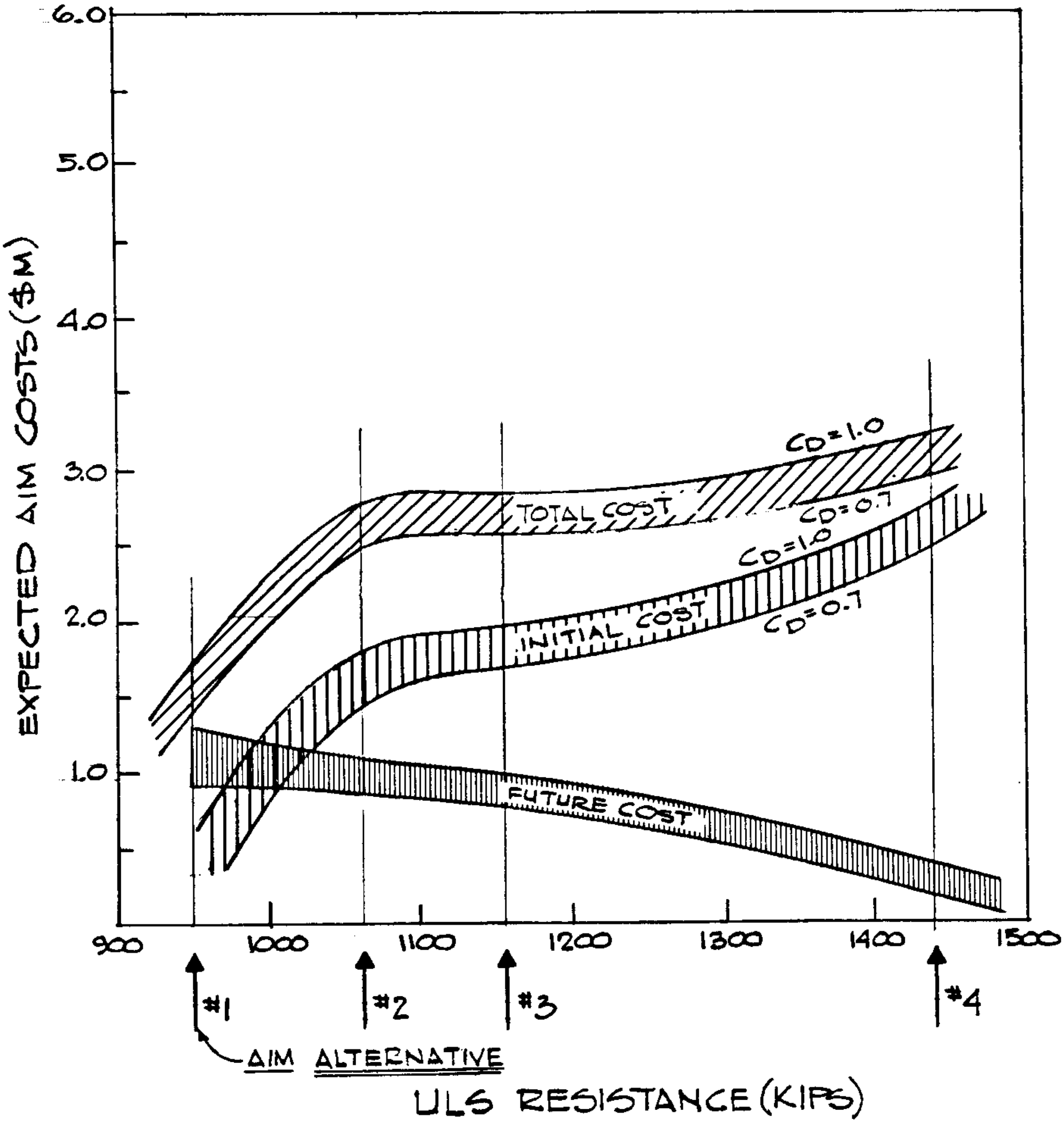
FIGURE 3-21

(Continued)



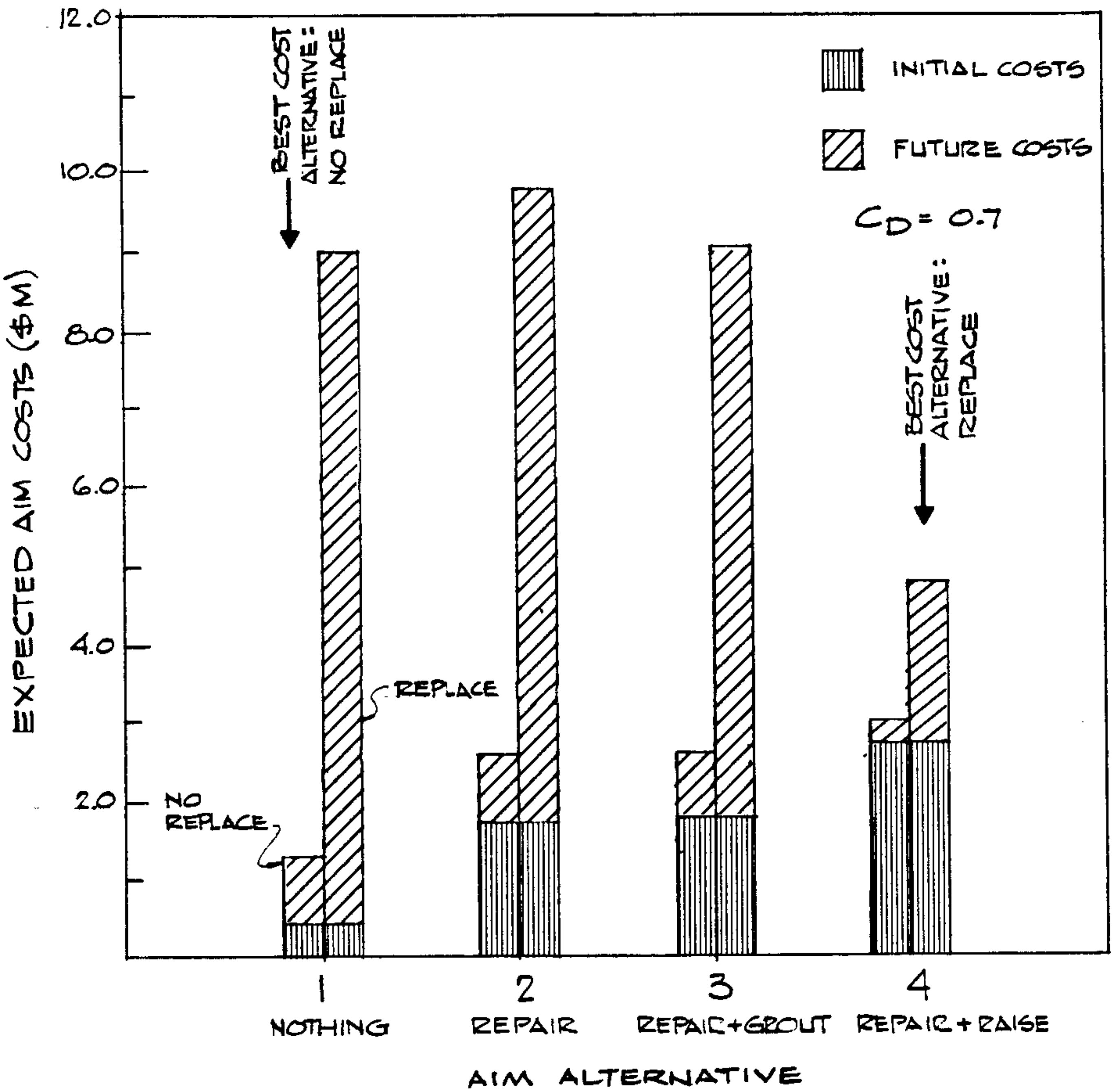
AIM COSTS WITH PLATFORM REPLACEMENT - PLATFORM "A"

FIGURE 3-22



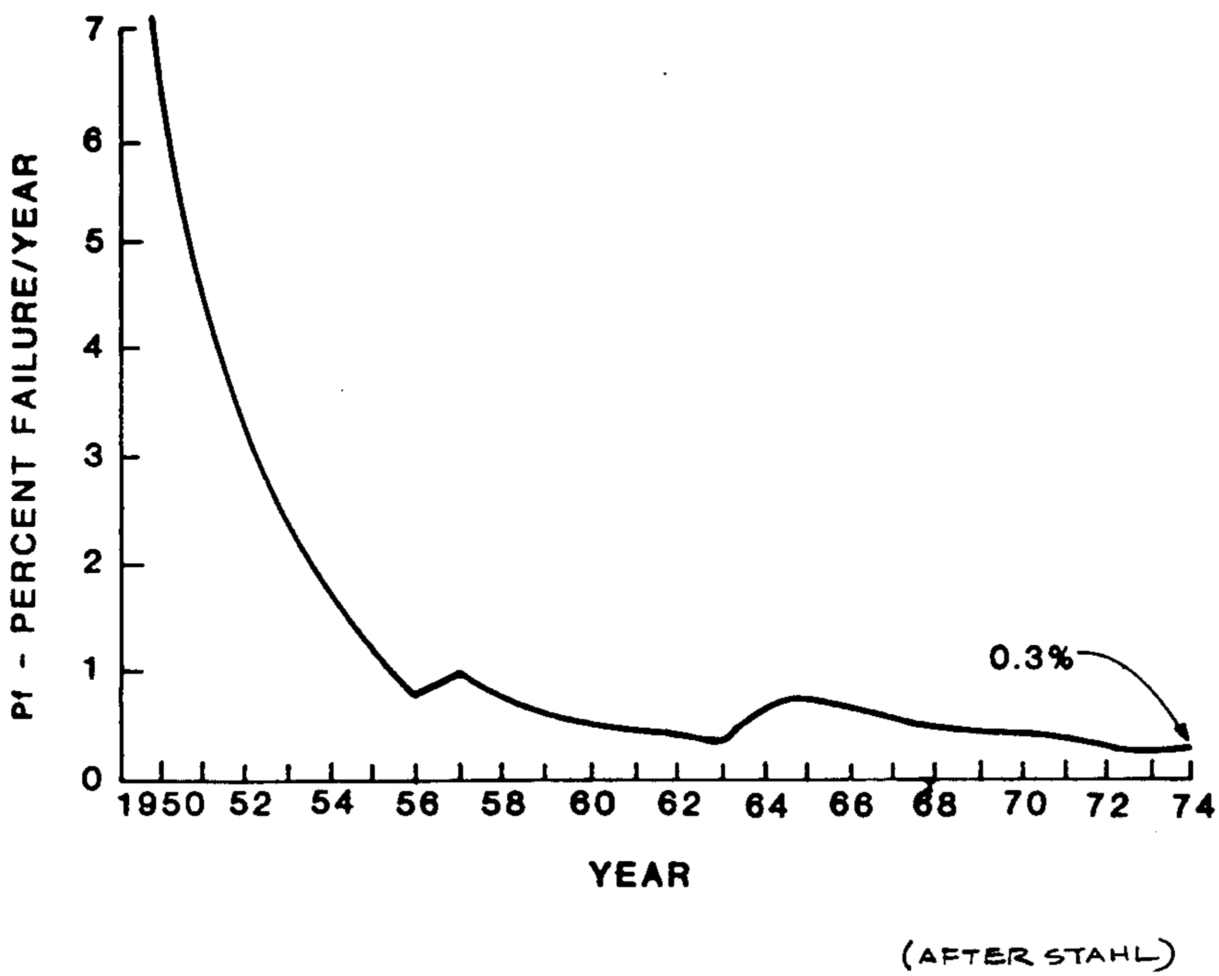
AIM COSTS WITHOUT PLATFORM REPLACEMENT - PLATFORM "A"

FIGURE 3-23



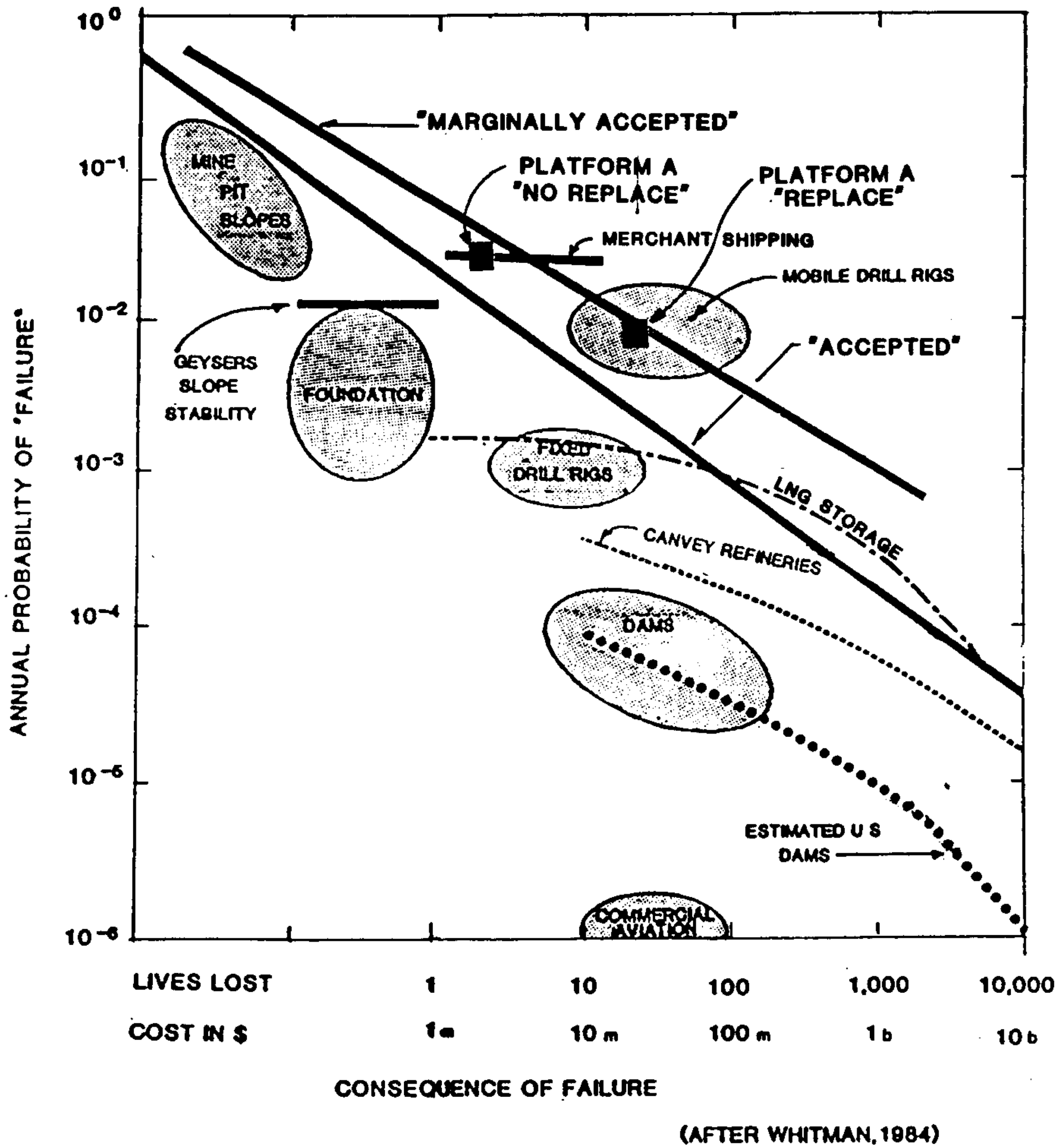
AIM COSTS - BAR CHART COMPARISON - PLATFORM "A"

FIGURE 3-24



HISTORICAL PLATFORM FAILURES - GULF OF MEXICO

FIGURE 3-25



HISTORICAL RISK DATA

FIGURE 3-26

4.0 PLATFORM "B"

This section describes the AIM process as applied to Platform "B". The section describes only the basic procedures, key points and key results of the process. Since many of the procedures are similar to those described for Platform "A" they will not be repeated here. Further details of the procedures and results are provided in Appendix B - "Platform "B" Evaluation."

4.1 Background Information

Figure 4-1 shows Platform "B" and describes some of its key features. Included in this figure are installation date, water depth, geometry and member sizes, soils, topsides and remaining economic life (Appendix B provides an expanded form of this data). The platform has automatic downhole shut-in equipment installed in the wells. Another interesting feature of the platform is the symmetric vertical diagonal bracing. Since all of the diagonal braces on both sides of the platform are battered in the same direction, the platform will exhibit different strengths in the longitudinal direction depending on whether these braces are in compression or tension.

Recent diver inspections of the platform turned up some limited damage as described in Figure 4-2. There is a separated horizontal at the +4 ft. elevation and several dented and cracked members also located at this elevation (again, see Appendix B for further details on this damage).

In general terms, the platform is about 30 years old, is unsymmetric in shape, has grouted legs/piles with no joint cans on the legs, has some minor damage and has a 5-year remaining economic life. Based upon this preliminary information, the platform has been chosen as a candidate for AIM assessment.

As discussed for Platform "A", the first AIM task is to gather all pertinent information related to the platform. This is accomplished by contacting the platform's engineering and operating groups as well as the original design vendor. This information is assembled and sorted and key facts and figures about the platform are recorded for future use.

Environmental data is also collected for the location as described in the following section.

4.2 Environmental Conditions

The two prime environmental conditions assessed for the site were oceanographic data and geotechnical data. These sets of information were developed from public and proprietary information [5 - 38] as well as input from several of the project participants, with the results summarized in the following paragraphs. All data was corrected for local effects at the platform site, such as water depth and coastal proximity.

Figure 4-3 shows the orientation of the platform in relation to the nearby Gulf Coast. Hurricane-generated waves can approach the platform from the south (+X) and east-west (Y) directions. From the northwest, however, the waves will be controlled by local winter storms instead of hurricanes. These local winter waves, limited in size due to the limited fetch created by the Gulf coast, are termed "Northers" throughout this study. This accounting of wave directions is particularly important for this platform due to the orientation of the braces (struts). For hurricane waves the struts will be in tension, and for the Northers, the struts will be in compression.

Wave height, wind speed, storm surge and current speed information was developed for the site. Figure 4-4 shows the wave height versus return period for the site. The hurricane wave height increases with return period until a height of about 43 ft. (40-year return period) at which point the waves are limited in size by the shallow water depth. The slight increase in wave height beyond this point is due to the increase in water depth due to storm surge which allows for a greater wave height prior to breaking. The platform, installed in 1959, appears to have withstood the effects of Hurricane Carla (1961) with a maximum wave height (at this site) of 44 ft. and a return period of 75 years.

Details on the hurricane wind speed, storm surge and current speed are provided in Appendix B. This data was developed such that the wind, surge and current are those that coexist during the same return period wave height. The waves, wind and current were assumed to act colinearly. Wind speed and current for the Northers were taken to be the same as for the hurricane. Storm surge was taken as zero for all Northers conditions since the Northers storms would likely draw water away from the coast creating a drawdown rather than a typical surge when water is blown toward the coast (since no recorded data was available for the Norther surge, a zero value was established for this study).

The Stream Function Wave Theory was used to determine the wave profile and water particle kinematics. The wave period was selected to provide a wave steepness (ratio wave height to length) of 1 on 12. Figure 4-5 shows the wave crest elevation versus return period as predicted by the Stream Function. The hurricane wave is seen to impact the lower deck at about a 28-year return period (the crest elevation curve also coincidentally makes a break at this point). The Northers do not impact the deck even at high return period intervals.

Figure 4-6 shows the wave profile for the 28-year return period hurricane and 100-year return period Northers wave. The hurricane wave is extremely "peaked" since it is at or very near breaking. This kind of wave profile results in large theoretical water particle velocities near the crest. The Northers wave is more conventional in shape.

As described for Platform "A", the Morison's equation was used to compute wave forces on the platform. The drag coefficient was set as 0.7 and an additional set of analysis was also run with the drag coefficient set to 1.0 for marine growth roughened tubulars. This provided a variation on the drag coefficient to determine its effect on the AIM evaluation. For the case of a wave in the deck, the drag coefficient was set to 2.0 for most members and equipment in the deck. The inertia coefficient was held constant at 1.5 for all cases.

Member diameters were increased to account for marine growth. Hydrodynamic forces were computed for water particle kinematics normal to a member. The current was not explicitly included in the force computations, similar to Platform "A".

The standard API RP 2A formulation (Eq. 2.3.2-1, 17th Edition [39]) was used to compute aerodynamic forces on the deck. The wind drag coefficient was taken as 1.0 for clean decks, 1.5 for cluttered but not "blocked" decks, and 2.0 for blocked decks allowing little or no light passage. Wind forces were disregarded when the wave crest was in the deck.

Figure 4-7 shows the general soil conditions at the site. This "log" was assembled from a boring taken at the site and from information inferred from other borings at nearby sites. The soils are characterized by 5-ft. of soft clay underlain by stiff clay to 115 ft., underlain by dense sand. The piles bear directly on the sand layer.

4.3 Environmental Forces

As discussed for platform "A", wave forces for this study were computed by a 2-dimensional wave grid moving past a full 3-dimensional computer model of the platform. The wave forces are used for two purposes. First, to generate force versus return period information for the platform and second, as a force profile to laterally load the platform until it reaches its ultimate state.

Figure 4-8 shows a perspective view of the 3-dimensional computer model for Platform B used for the wave force analysis. At this point, the model contains only the geometric features of the platform (member location, length, diameter and hydrodynamic coefficients) since the current purpose is to only determine wave loads. The deck framing is modeled in some detail with modeled members incorporating the wave area for members not explicitly modeled. Wave area for the deck equipment is distributed along the major horizontals at each deck elevation.

Figure 4-9 shows the hurricane wave force profiles (-X, Y directions) developed for the wave just below the lower deck (28-year return period). Also shown is the force profile for the 100-year Norther. This return interval was selected as a matter of convenience for comparison purposes since the Norther waves never approach the deck level. The profiles are constructed by summing the nodal loads at each horizontal elevation. The profiles bulge at the water line due to appurtenances such as boat landings, barge bumpers, and walkways.

The total force on the platform for the 28-year RP hurricane waves is 650 kips in the -X direction and 1020 kips in the Y direction. The 100-year RP Norther wave has a total force of 300 kips. As expected, the loads in the Y direction are much greater since the wave front concurrently acts across a greater portion of the platform for this direction (i.e. the wave crest is hitting more members at the same time when it is perpendicular to the long axis of the platform).

Figure 4-10 shows the completed results of the environmental force analysis to determine force versus return period for the X direction. Figure 4-11 shows similar information for the Y direction. The range of forces are shown for a drag coefficient of 0.7 and 1.0. The analyses were run for the case with and without the deck. For the case without the deck, the same computer model was used except for elimination of the wave area for the deck framing and deck equipment.

Note that both hurricanes Carla and Alicia apparently developed maximum wave heights that should have brought the crests close to or into the lower deck. The platform history contains no mention of damage associated with these storms. Either the platform records are incomplete, or the oceanographic estimates of the wave heights (surge and crest elevations) are too high. In any case, it would appear that this structure has survived two proof loadings at or near its ULS capacity.

The waves to the right of the vertical line at the 28-year return period are waves that are into the deck. The dashed lines indicate the true results of the wave force analysis. That is, the analysis showed that waves that are just a fraction into the deck result in a sudden finite "jump" in the total force curve. This is caused by the limitations in discrete computer modeling, where the wave area for the deck equipment is lumped onto the horizontals at each deck. Thus as soon as the wave crest, with its high water particles velocities, is into the deck, the computer model considers all of the deck equipment to be loaded by the waves. In reality, only a limited portion of the equipment would be loaded by the waves.

Therefore, it was decided to create a smooth transition between a wave below the deck and into the deck by interpolating a straight line between the deck elevation (+39.6 ft.) and an elevation two-thirds into the lower deck (+48 ft.). The two-thirds of deck height was selected because most of the equipment would be completely covered by a wave of this height. The wave height return period resulting in a 48 ft. crest is approximately 500 years (Figure 4-5). The wave forces are therefore smoothly transitioned between the force for a wave just below the deck (28 years) and a wave acting on all of the equipment (500 years). This provides a more realistic distribution of forces as the wave moves into the deck. This transition was not required for the Northers since they do not impact the deck.

The slight decrease in the computer generated force at the deck (dotted lines) is again caused by discrete computer modeling and the steep shape of the wave profiles. The larger waves have a greater crest water particle velocity, but at the location of the computer modeled deck equipment, a smaller wave may have a larger velocity (see Appendix B). The force due to a wave just into the deck is therefore taken as the upper limit of forces on the platform. Considering the large magnitude of the force "jump" due to waves in the deck, this approximation has little effect on the results.

The resulting final force versus return period curve for the platform is indicated by the shaded region. The force curve is seen to increase with return period and then take a substantial increase as the waves start acting on the deck. The upper and lower bounds of the shaded curve reflect the variations in drag coefficients.

An additional force curve for the condition of no marine growth and removal of several boat landings is shown for the Y direction waves (Figure 4-11). This additional force data was required for one of the AIM alternatives which looked at reducing forces on the platform. This is further discussed in Section 4.4.

4.4 Platform Capacities

The wave force profiles discussed in Section 4.3 are used for the overload analysis to "push" the platform until failure is reached. For this study, it was decided to use the profile for the hurricane wave just under the deck (28-year return period) and the 100-year wave for the Northers. The selection of just one profile (for each direction) was required since overload analysis can accommodate the ramping (i.e. continual increasing of load) of just one load profile at a time.

In order to most properly capture the ultimate capacity of the platform, a nonlinear model must be developed. This model contains specialized elements that reflect the limit state behavior of the platform members in terms of limit capacity and post limit capacity. These capabilities also require special structural analysis software to control the force applications and load redistributions as the platform members fail. This study used the PMB developed computer program SEASTAR.

Figure 4-12 shows a perspective of the Platform B model and indicates the types of elements used in the various regions of the platform. Also shown is the type of force-deformation for each element. A description of the special SEASTAR elements used in the analysis is provided for Platform B and summarized below. Appendix C provides a more complete description of the computer modeling.

<u>Note:</u> This section presents platform B capacities for the "original" platform computer model discussed at the July AIM meetings. Subsequent review of this computer model indicated that the deck legs were modeled with insufficient stiffness, resulting in a "soft" structure (large displacement for a given load). However, a reanalysis of the platform with the proper leg stiffness indicated little change in the ultimate platform capacity (Appendix B). The result is little or no change in the AIM alternative evaluation when using the "original" or corrected ULS results.

SOILS - PSAS (Pile Soil Analysis System) elements [41]. These nonlinear elements reflect the axial and lateral force-deformation characteristics of the soils surrounding the piles.

PILES/CONDUCTORS - Nonlinear beam elements. These elements reflect the elastic-plastic relationship for beam-columns that fail by yielding (no buckling).

LEGS - Nonlinear beam elements. Same modeling as piles/conductors.

BRACES - Nonlinear truss elements. The slender brace members are governed primarily by axial loading with very little bending. They are likely to fail in buckling or punching through the leg. A nonlinear truss was used to model an elastic perfectly plastic response at the calculated buckling stress for a member. This type of modeling (for the platforms analyzed in this study) is believed to provide a close approximation to the ultimate state behavior of the platform (see Appendix C). Since this structure has grouted legs, the braces were generally found to buckle prior to punching through the leg.

DECK - Linear beams. Since the deck was modeled to primarily to capture wave loads and to distribute loads between legs, the deck members were modeled as linear beam elements.

Once the platform model has been defined and all member properties have been established, the overload analysis can proceed. As previously mentioned, a static analysis was performed with the platform's load levels slowly incremented until platform failure.

As discussed for Platform A, the material yield strength was increased to 45 ksi from 36 ksi for A36 steel to account for expected yield strengths and strain rate effects.

Figure 4-13 shows the deflected shape of the platform just prior to failure for loading in the X direction. At this point, the full magnitude of the wave below the deck forces has been applied to the platform and the deck is starting to take load from the deck wave load vector. There is some displacement in the piles but no yielding.

Figure 4-14 shows the X direction force-displacement history at the deck level for the as-designed condition. The platform is seen to displace in a linear (elastic) fashion at initial loading.

The hurricane response curve flattens (more ductile) at the the point of application of the wave load acting to the deck. This larger deformation for a given force magnitude is due to the application of loads high up on the platform (the previous wave below the deck loads were primarily applied along the submerged portion of the platform). The first members (legs below the deck) begin to yield after application of the deck wave loads. The platform is considered to have reached the ultimate state after multiple leg failures occur at a load of 1135 kips. The return period associated with load level is 115 years per Figure 4-10 (C_D = 0.7).

The Norther response steadily increases until the braces (struts) buckle along the bottom rows and then the top rows at a load magnitude of 1440 kips. The return period associated with this loading is greater than 5,000 years. The ultimate load level reached by the Norther waves is higher than that due to the hurricanes because the hurricane load severely penalized the platform's performance due to the waves impacting the deck. The Norther condition did not consider waves in the deck. If the hurricane condition had been analyzed in the Norther direction (+X), the platform would have reached a lower ultimate state than the true hurricane direction (-X) since the diagonal braces buckle at a lower load than they yield in tension (or tear from the leg joint).

Figure 4-15 shows the deflected shape of the platform just prior to failure for loading in the Y direction. The Y direction loading results in a slight twist of the structure due to the resistance provide by the conductors between rows 2 and 4.

Figure 4-16 shows the Y direction response of the as designed platform due to hurricane waves. The figure reflects an initial elastic response with slight curvature due to yielding of the soil elements. Several braces then begin to buckle followed by leg yielding to achieve an ultimate capacity of 760 kips. Notice that this capacity is reached prior to the waves impacting the deck. The return period associated with this load level is 12 years per Figure 4-11 ($C_D = 0.7$).

Similar analyses are performed for the structure for the AIM alternatives investigated in this study. These can be summarized as follows:

Alternative 1: As-Is. Leave the platform as-is with the damage shown in Figure 4-2. This requires modification to the platform computer model to reflect the damaged members prior to a new overload analysis (see Appendix C, [56]. Figure 4-17 shows the result of the damaged overload analysis. The initial stiffness of the structure is slightly lower (due to the separated member), but the response of the structure is essentially the same as for the as-designed condition. The corresponding return period remains as 12 years.

Alternative 2: Remove boat landing and marine growth. The two boat landings in the longitudinal directions (perpendicular to the Y-wave) will be removed. This leaves one boat landing along X-direction at row 1. Also remove marine growth on a regular basis. This results in a limit state capacity the same as the as-designed condition; however, the return period of the force is increased to 20 years, per Figure 4-11 (the w/o Boat Landing and Marine Growth curve, $C_D = 0.7$).

Alternative 3: Repair damage. Return the platform to the as-designed condition. This has little effect on the platform's capacity so the return period for this condition remains the same (12 years).

Alternative 4: Raise deck and make all repairs. The as-designed computer model was used for this analysis. Since this case does not consider waves in the deck, only the wave profile forces were continually increased for the analysis. Figure 4-16 shows the response of the platform. There is a significant increase in capacity for the X-direction hurricane waves, but since the platform fails prior to waves in the deck for the Y direction, this AIM alternative has little effect for Y hurricane waves. The corresponding return period is again 12 years.

4.5 AIM Alternatives Evaluation

The AIM approach suggests two frameworks for making evaluations of alternative AIM programs: (1) Industrial (Commercial) Cost-Benefit framework and (2) Public (Regulatory) Historical Standard of Practice framework. These two approaches have been discussed in detail in Section 3.5 for Platform A. This section describes these approaches as applied to Platform B.

4.5.1 Cost-Benefit Evaluation

Figure 4-18 compares the total initial AIM costs for each of four alternatives for Platform B. Alternative 1 (AIM-1, As-Is) provides the lowest initial cost while Alternative 4 (AIM-4, Repair and Raise Deck) provides the highest initial cost. Figure 4-19 shows the expected future costs for Platform B. The background data used to develop these costs is similar to that discussed for Platform A (Section 3.5.1). Further details of these costs are provided in Appendix D.

Figure 4-20 shows an example computation of total expected costs for AIM Alternatives 1 through 4. The example assumes a 5-year remaining life (Figure 4-1), platform replacement in the event of failure and a C_D of 0.7. Also indicated is a maximum wave height of 46 ft. with a return interval of 275 years (Figure 4-4) (caused by wave breaking due to the shallow water depth). The initial cost is $0.15 M (Figure 4-18). The platform's ultimate capacity for this alternative is 760 kips controlled by the Y direction hurricane, (Figure 4-17). The return period associated with this ultimate capacity is 12 years (Figure 4-11) ($C_D = 0.7$). The future cost is the sum of the restoration cost ($2.0 M) plus the replacement cost ($17.2). The total cost can then be computed as the initial cost ($0.15 M) plus the annual probability of failure (1/12) minus the annual probability of the upper limit on loadings (1/275) times the remaining platform life (5 years) times the cost of failure ($19.2 M). The assessment for Alternative 2 follows in a similar manner.

The modification of the annual probability of failure (1/12 to 1/275) to account for the breaking limit in wave heights provides an estimate of the truncation effects of the probability distribution [1].

A final comparison summary of the AIM cost evaluation is shown in Figure 4-21 for the cases with and without platform replacement. The AIM alternative of removing boat landings and marine growth appears to be the best alternative for both cases. The variation in drag coefficient (C_D = 1.0) did not have any effect on the results. Thus for this platform, which shows a fairly low margin of safety (20-year return period event) and a short future life (5 years), the AIM process indicates a "moderate" amount of funds should be utilized to ensure the platform's safety for its expected remaining life.

An alternative evaluation of the future costs could be based on the premises that the platform operator/owner has already included the costs of abandonment in an accrual fund, and that there will be additional costs associated with deferred production and well control in the event of failure (refer to G. C. Lee evaluation, Appendix E). The total future cost changes from $19.2 M (Figure 4-19) to $30.2 M (Appendix E). The relative ranking of the AIM alternatives due to this modification remains unchanged for the replacement and non-replacement options.

The net value of the facility is estimated to be approximately $21 M (Appendix E). The expected total cost of the AIM program is about $5 to

\$7 M (Alternative 2) with an initial cost of about \$0.4 M. The AIM program initial cost represents about 2 percent of the net value of the facility, and would appear to be a justified expenditure from an investment standpoint.

Another evaluation could include considerations of uncertainties in initial and future costs. For example, the coefficient of variation (ratio of Standard Deviation, σ, to mean value) associated with the AIM-2 alternative initial costs (Figure 4-18) might be estimated as 30 percent, i.e.,

$$+1\ \sigma\ CI = 1.3 \times \$.35\ M = \$.46\ M$$

The Coefficient of Variation associated with the estimated future costs associated with replacement (Figure 4-19) might be estimated to be 80 percent, i.e.,

$$+\ 1\ \sigma\ CF = 1.8 \times \$19.2\ M = \$36.6\ M$$

The resultant Coefficient of Variation of the total expected cost of \$4.8 M would be approximately 85 percent, $(.3^2 + .8^2)^{1/2}$. This would indicate a $\pm 1\ \sigma$ total cost range of \$.72 M to \$8.88 M. The rank order of the AIM alternatives remains unchanged; however, the decision maker now has an appreciation of the potential up-side and down-side economic implications of each alternative.

There are many different economic evaluations that can be made in this framework and only several have been illustrated here. The "best" evaluation is one that also incorporates the concerns and judgments of the decision makers. Performing systematic parametric sensitivity analysis on the technical and evaluation factors to determine their influences on defining the "best" alternative is an essential part of the decision-making process.

4.5.2 Historical, Standard of Practice Evaluation

The second process for reaching decisions/judgments concerning the suitability of a particular AIM program has been defined [1] as an historical, standard of practice (calibration) evaluation. This process is particularly attractive in public and regulatory evaluations/ justifications.

The basic premise of this process is that through experience, engineers, constructors, and operators have developed consensus guidelines and standards of practice that represent professionally acceptable solutions, recognizing industrial, regulatory, and general public interests and objectives.

Based on the commercial evaluation, the most attractive AIM alternative is a load management option (Alternative 2), removing unnecessary boat landings and removing marine growth. This option results in an expected total cost/consequence of $4.8 million (Figure 4-20) to $7.4 million (Appendix D), or a total future cost (not probability weighted) of $19.2 to $30.2 million.

Figure 3-25, described in Section 3.5.2, summarized the historical statistics on failures of major drilling and production platforms in the Gulf of Mexico [49]. The illustration indicates that following the mid-1950's (after Hurricane Hilda), the aggregated structure performance in the Gulf of Mexico has reached a failure rate of less than 0.3 percent per year. Experience through 1987 would indicate an average failure rate approaching 0.1 percent per year.

An extension of the information contained in the Gulf of Mexico platforms failure rate (Figure 3-24) has been provided by Whitman [53] (Figure 4-22). This information addresses offshore fixed and mobile drilling platforms in the context of world-wide experience and in reference to other engineered structures (industrial and public sectors). Most importantly, the ranges of consequences associated with the ranges of failure rates are identified (including potential economics ranges and injury ranges).

This information provides a potentially strong basis on which to judge "suitability for service," given a particular AIM program/strategy.

The region that divides acceptable from unacceptable risks and consequences (lines labeled "acceptable" and "marginally acceptable") represent these investigators evaluation of what society has determined as an equitable or reasonable trade-off of costs and risks. The "acceptable" and "marginally"acceptable risk rates (annual, $P_{fa/A}$) are related to the economic/cost consequences (CT) according to equations 3-1 and 3-2 (Section 3.5.2), respectively.

The most attractive AIM alternative for Platform B in the case of platform replacement was to remove particular boat landings and periodically remove marine growth (AIM-2, Figure 4-21). In this condition, the failure rate was estimated as 5.0 percent per year (20-year RP) and the loss of serviceability consequences estimated as

$19.2 M. The failure rate for this scenario would be excessive if the historical Gulf of Mexico platform failure rate (P_f = 0.1 to 0.3%) were used.

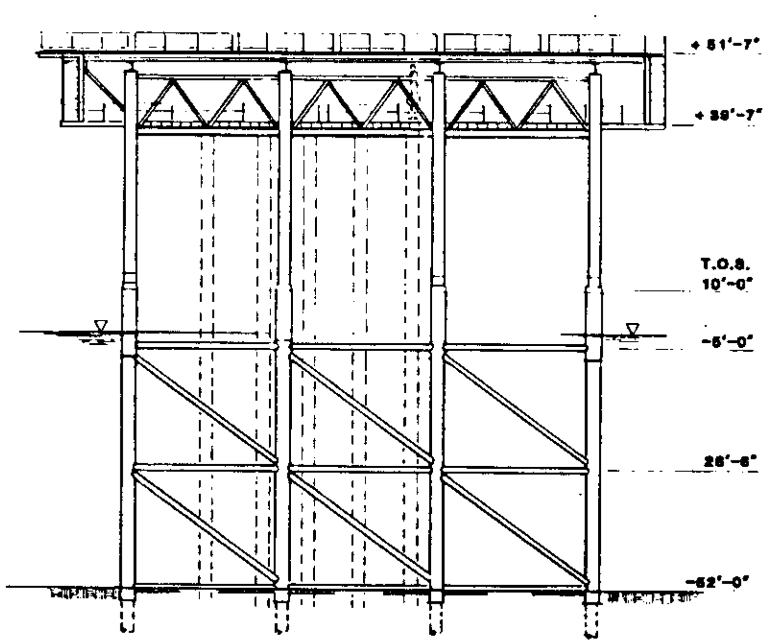
The more comprehensive valuation involving both risks and consequences would indicate target risks of 0.19% for the "acceptable" (Eq. 3-1), 1.4% for the "marginally acceptable" (Eq. 3-2) conditions. Thus, this alternative (P_f = 5.0%) would apparently fail to satisfy the risk-consequence based valuations.

In the case of the non-replacement scenario, the most attractive alternative (AIM-2, Figure 4-21) is the same as the replacement case with a computed failure of 5.0 percent per year. The total cost consequence for the non-replacement case is $2 M. This alternative would fail to satisfy the historical Gulf of Mexico platform failure rate (Figure 3-24), but it would qualify when the risk-consequences were evaluated (P_f = 1.1% to 6.6%).

A paradox in this evaluation is that the platform has successfully withstood wave forces from two hurricanes generating breaking wave conditions (return periods greater than 28 years). Hurricane Carla had a site return period of about 100 years. This would imply a platform probability of failure of less than 1 percent. This experience would indicate that this platform could qualify for service on the basis of a marginal risk rate/consequence combination (less than 1.1 to 1.4 percent per year and $20 to $30 million consequences given a failure).

Given a justifiable, historically based definition of an "acceptable" and "marginally acceptable" combination of risk rate and consequences (e.g., Figure 3-25, Eqs. 3-1 and 3-2), a regulator/operator could determine if the structure and its proposed AIM program meets the defined guidelines for the required standard of practice in requalifying platforms. If the platform could be brought to the standard of practice guidelines using a particular AIM program, then the regulatory justification could be facilitated. It would then be up to the platform operator to demonstrate to his company that the platform operations, its AIM program, and its income producing potential were a justifiable business venture.

- o Installed 1959
- o 52-ft Water Depth
- o 8 Legs (30" Diameter, 0.5" Deck Legs,
  33" Diameter, 0.5" Jacket Legs)
- o 7 Wells (5 Inboard, 2 Outboard)
- o Oil Production
- o Single Diagonal Braced (12.75" Diameter, 0.33")
- o Damaged Braces
- o 30" Diameter Piles (8), Grouted
- o 5-ft Soft Clay Underlain by Stiff Clay to 115 Ft,
  Underlain by Dense Sand
- o Lower Equipment Deck at +39 Ft
- o Unmanned
- o 5-Year Remaining Economic Life



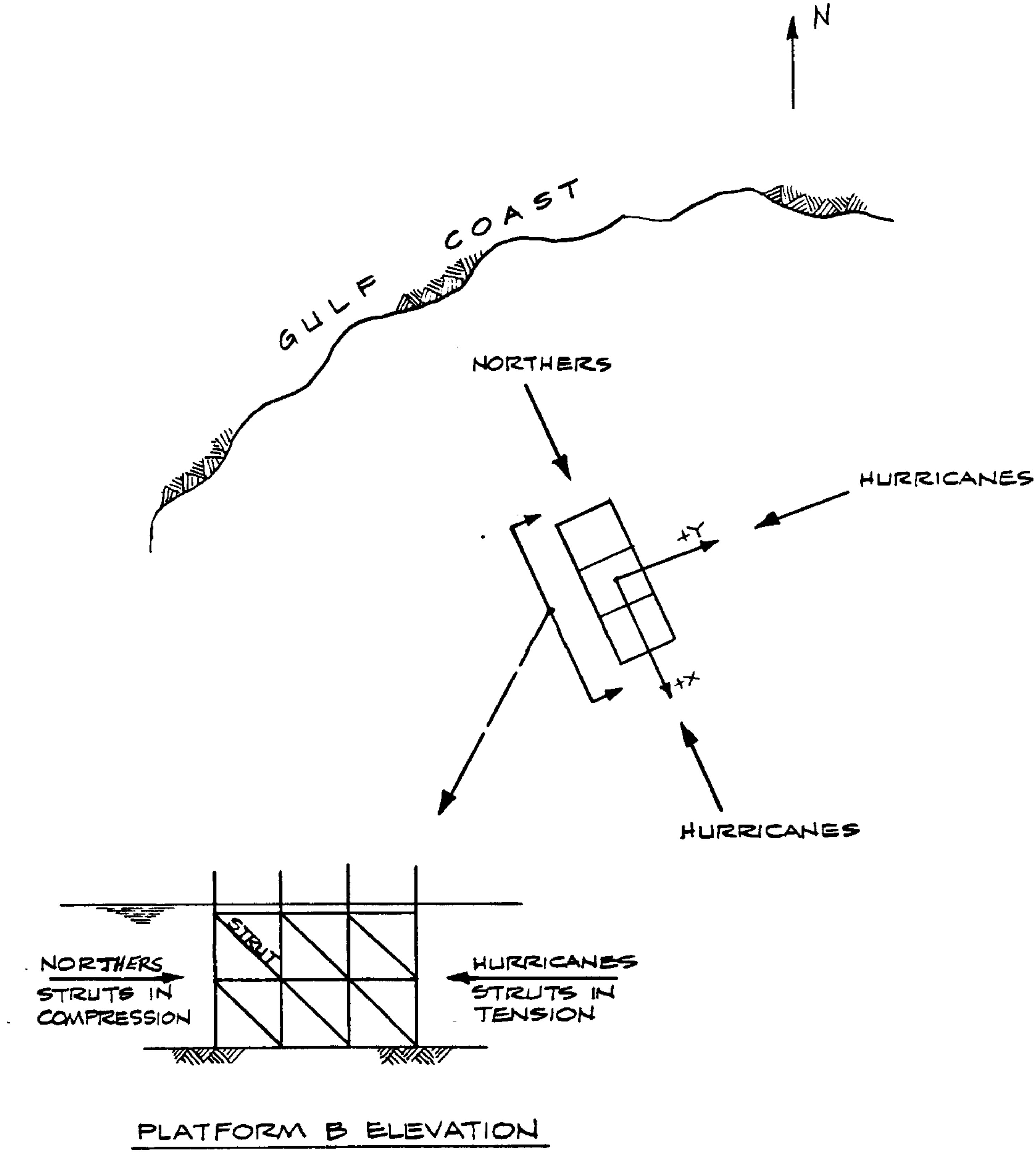
PLATFORM "B" DESCRIPTION

FIGURE 4-1

ITEM NO.	LOCATION	DAMAGE
1	Horizontal Face Member Row B B2 to B3 at -4′	Complete Separated from Leg at B2 Numerous Dents
2	Horizontal Interior Diagonal -4′ B3 to A2	Cracked at B3 from 11:30 to 4:30 Crack Length = 20"
3	Horizontal Face Member Row B B4 to B3 at -4′	Dent 56" x 11" x 2" Deep 4" Crack on Bottom of Dent
4	Horizontal Face Member Row A A3 to A4 at -4′	Dent 10" x 8" x 1/2" Deep

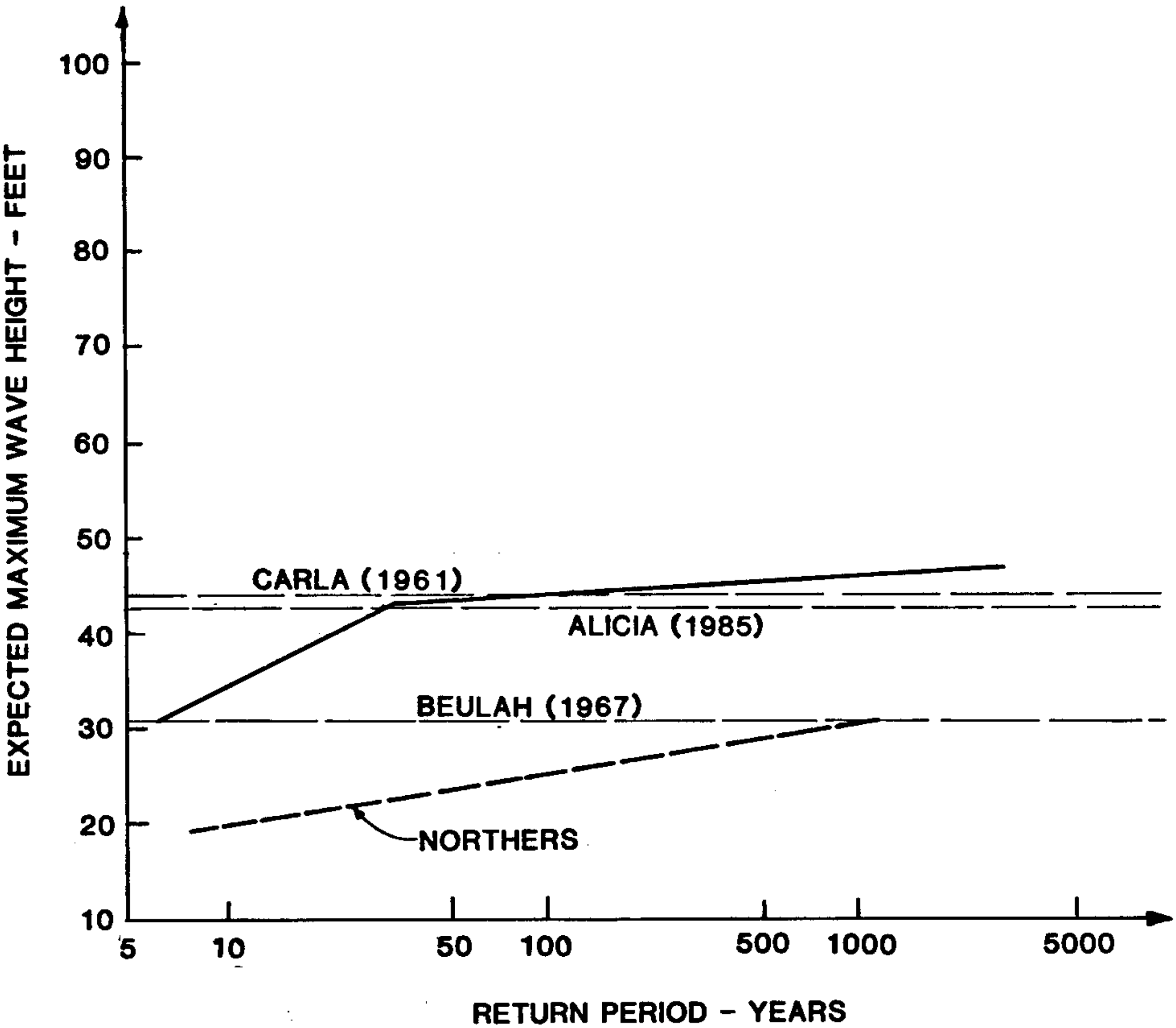
PLATFORM "B" DAMAGE REPORT SUMMARY

FIGURE 4-2



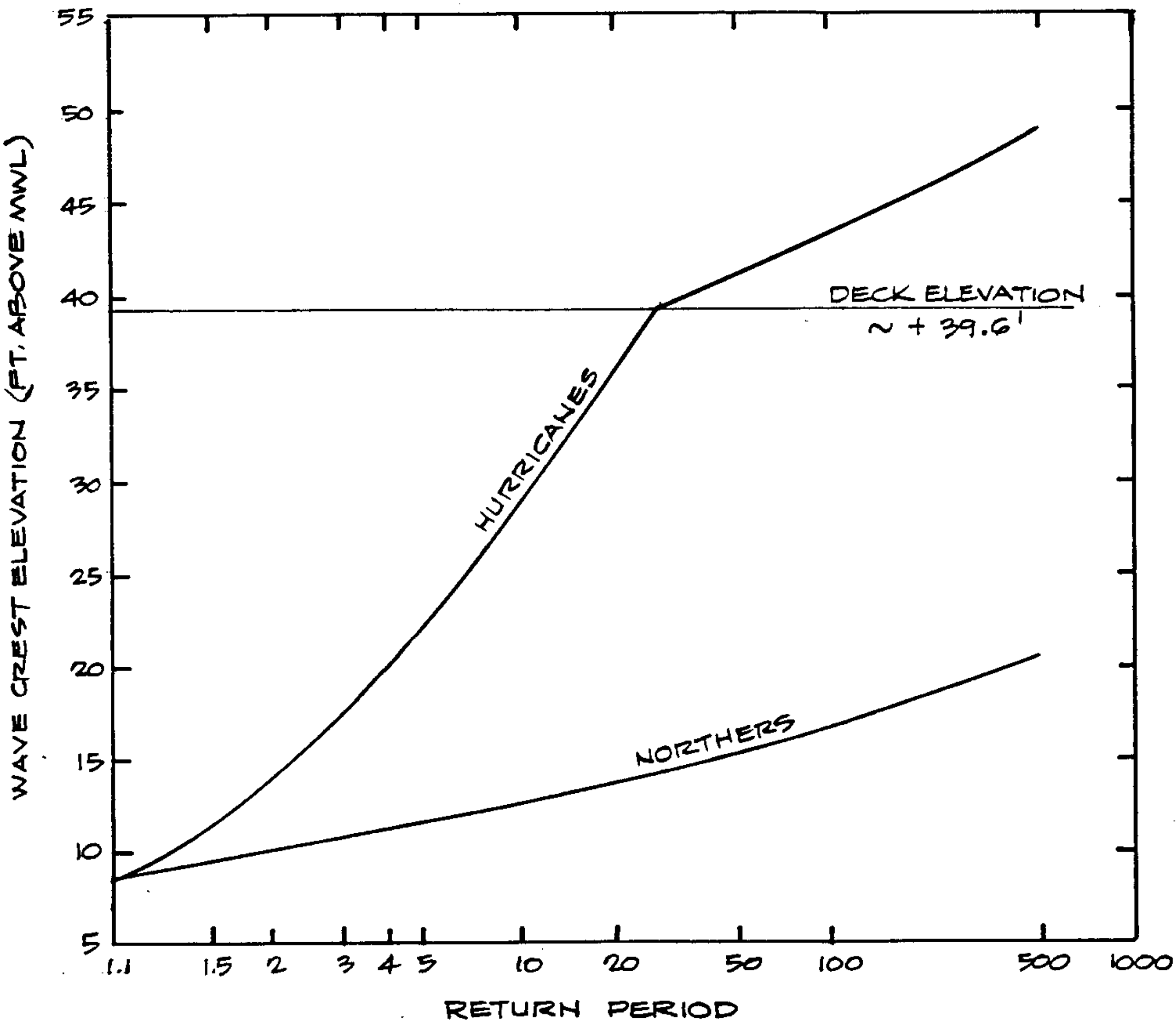
PLATFORM "B" LOCATION

FIGURE 4-3



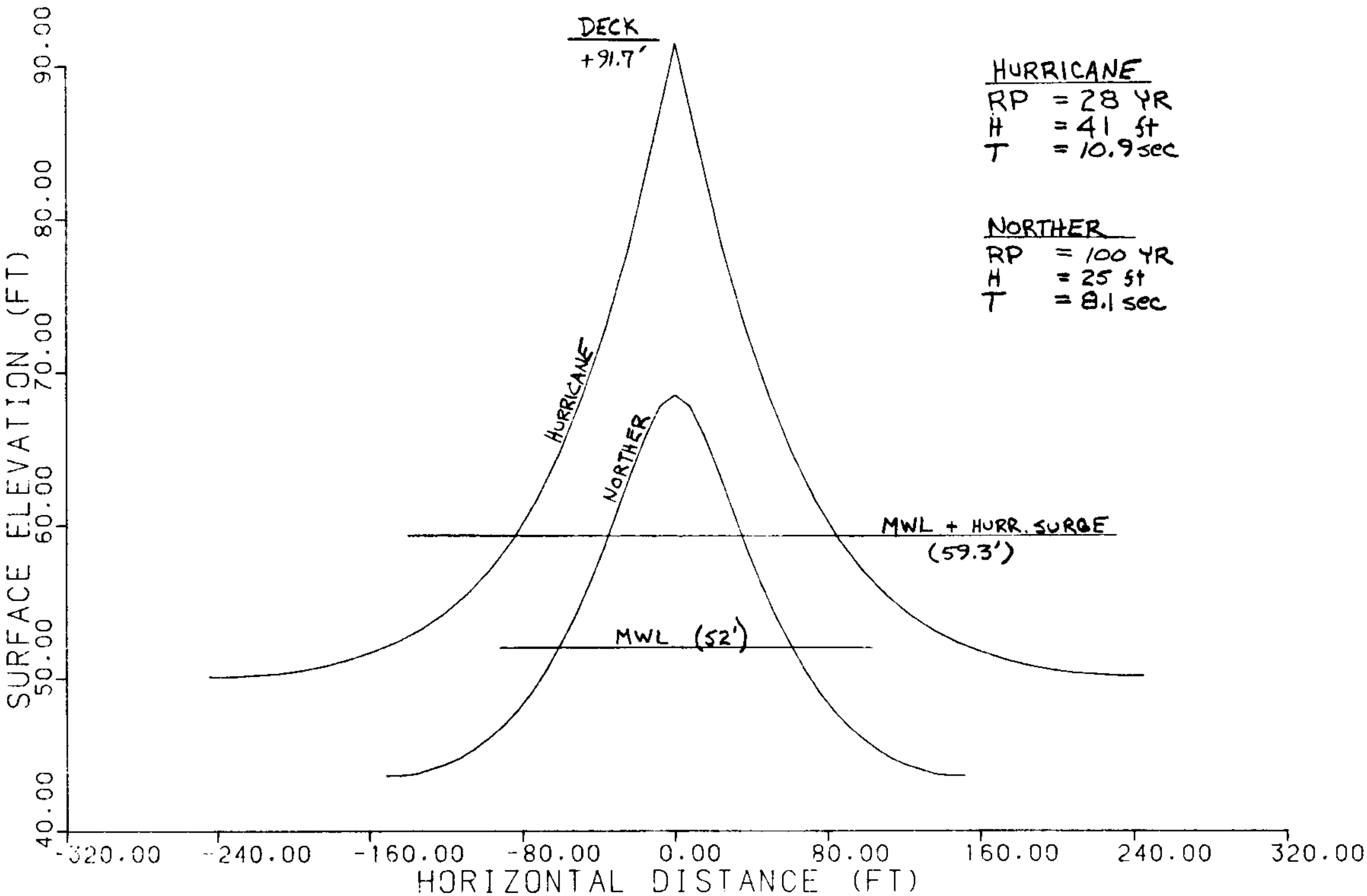
WAVE HEIGHT VS. RETURN PERIOD - PLATFORM "B"

FIGURE 4-4



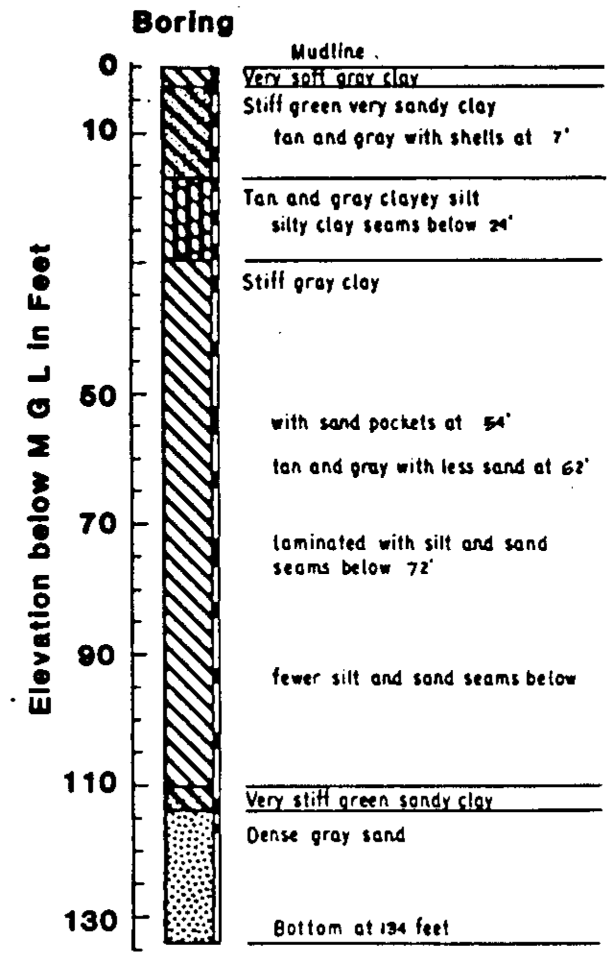
WAVE CREST ELEVATION - PLATFORM "B"

FIGURE 4-5



WAVE PROFILES - PLATFORM "B"

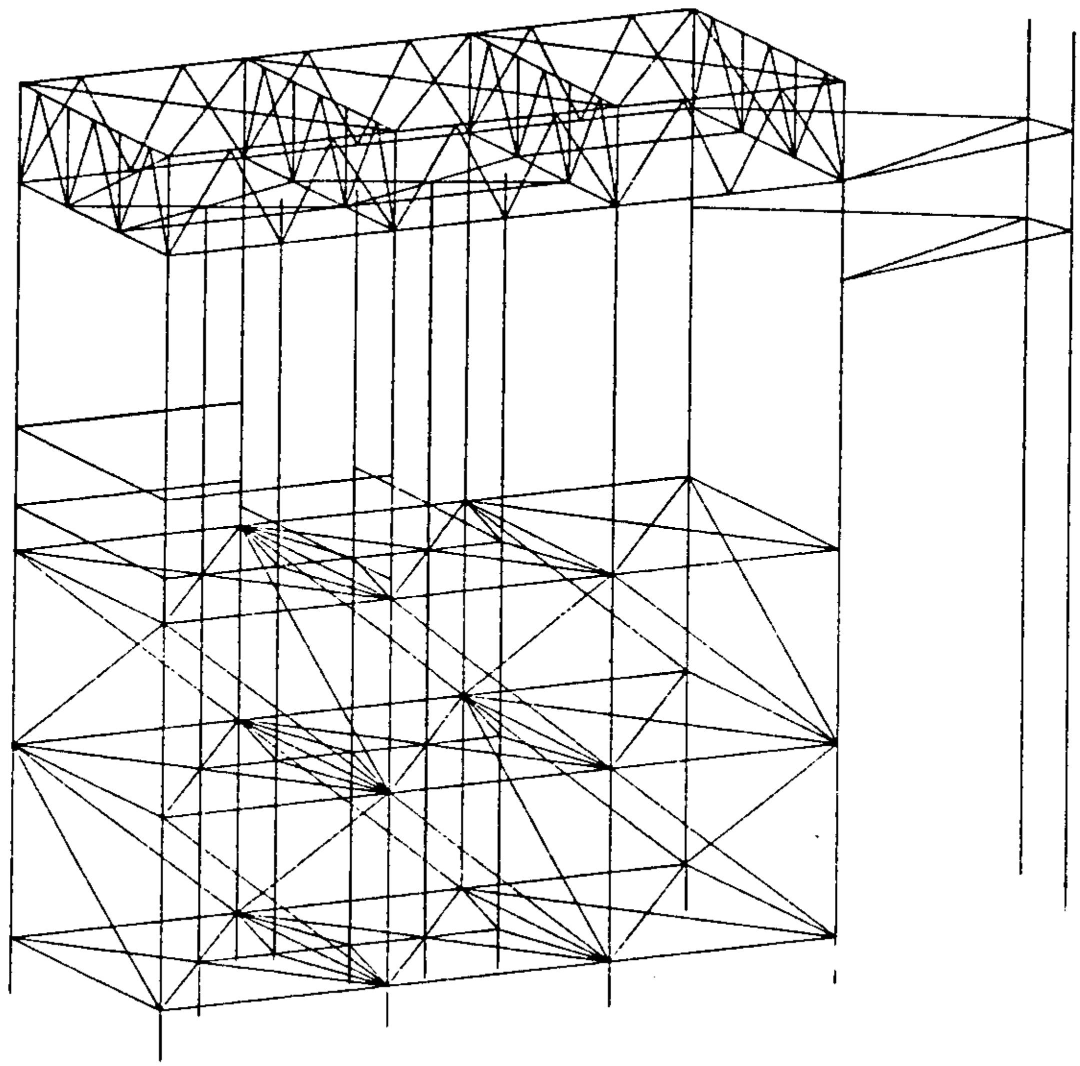
FIGURE 4-6

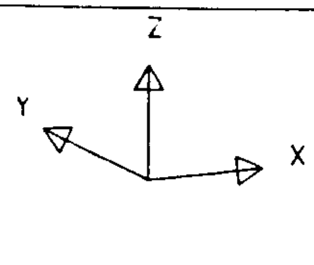


SOIL CONDITIONS - PLATFORM "B"

FIGURE 4-7

PMB Systems Engineering Inc. San Francisco, Calif. 94111





3-D COMPUTER MODEL - PLATFORM "B"

FIGURE 4-8

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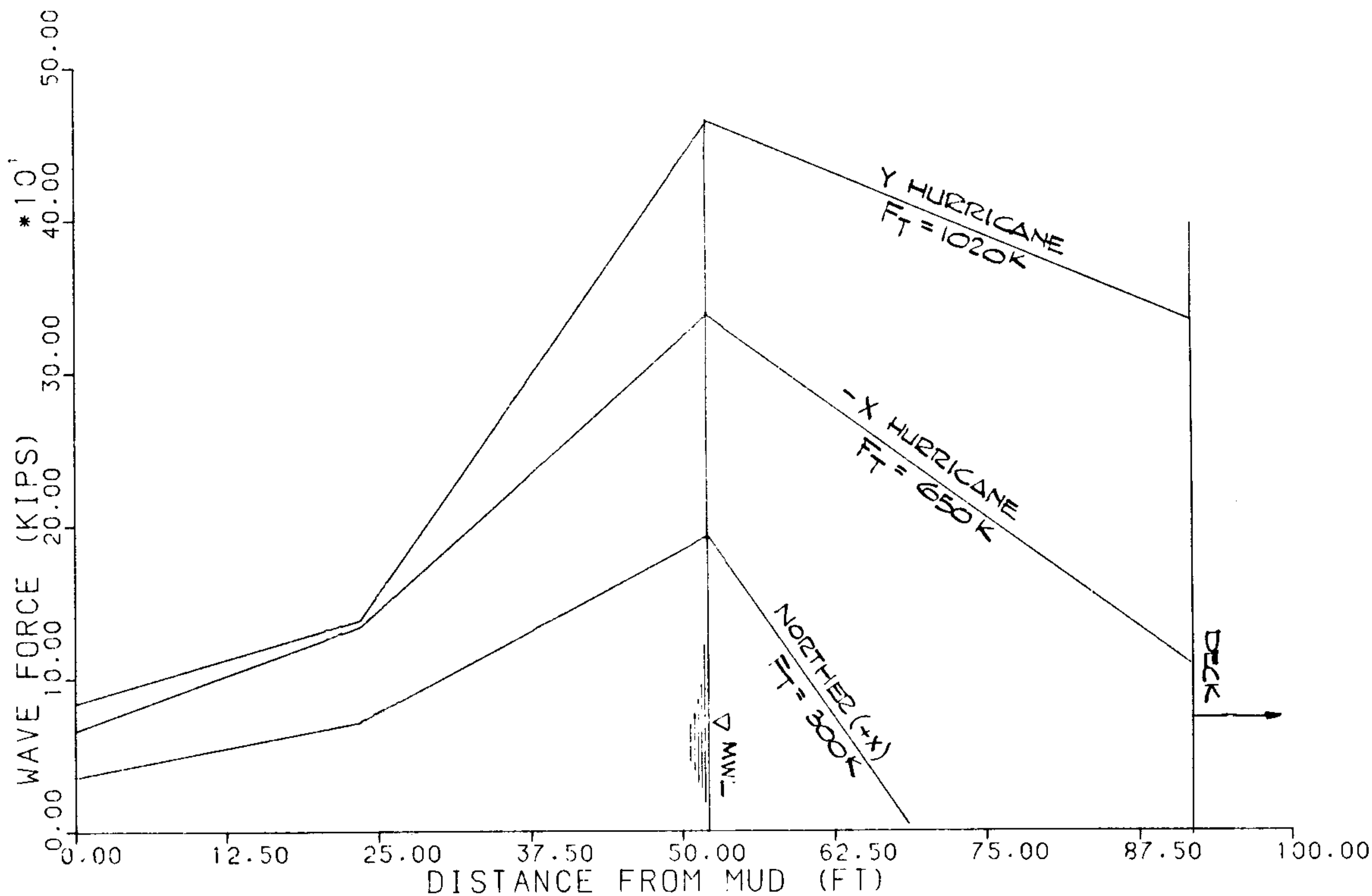
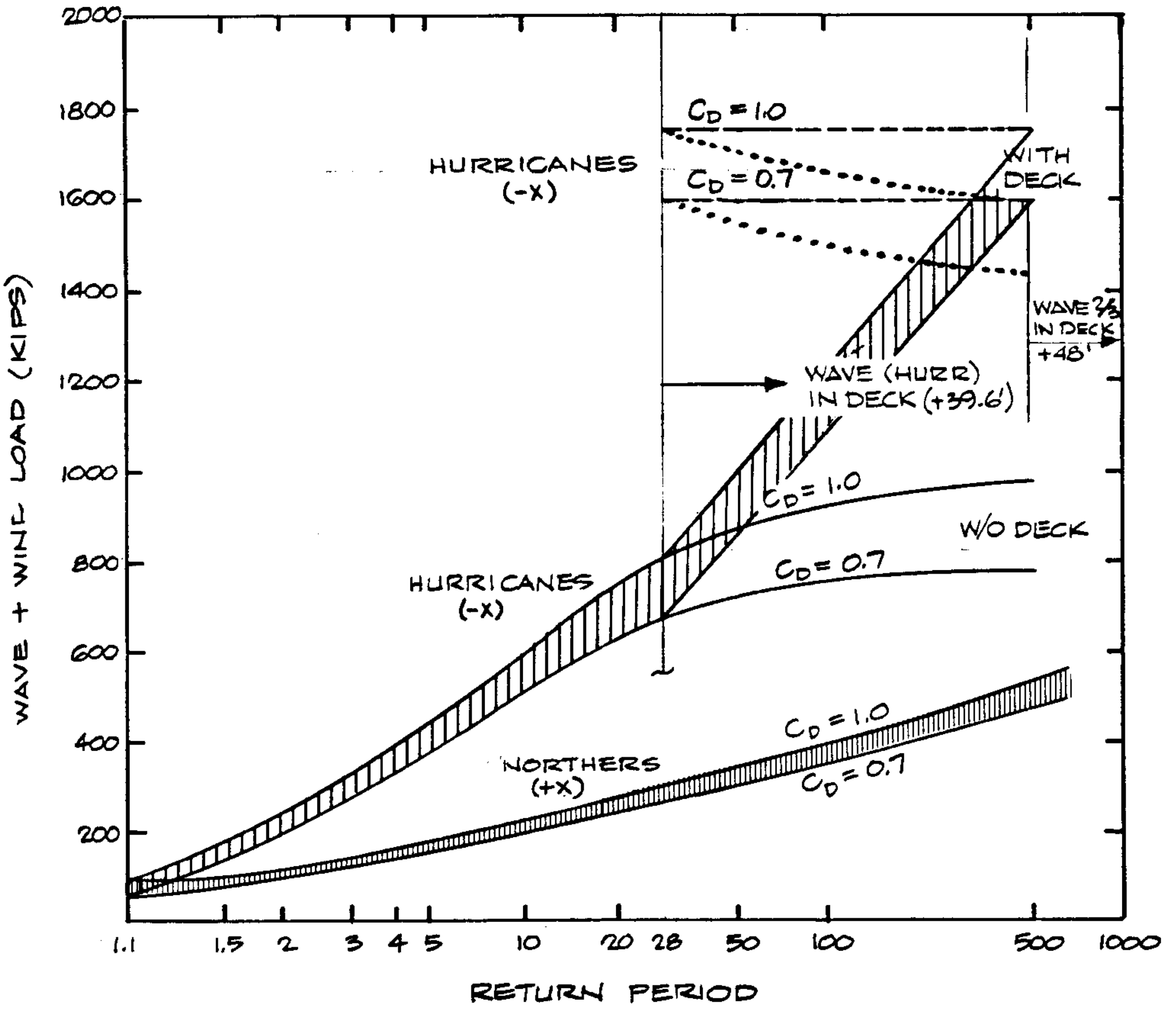
TIME - 14:34:24



WAVE FORCE PROFILES - PLATFORM "B"

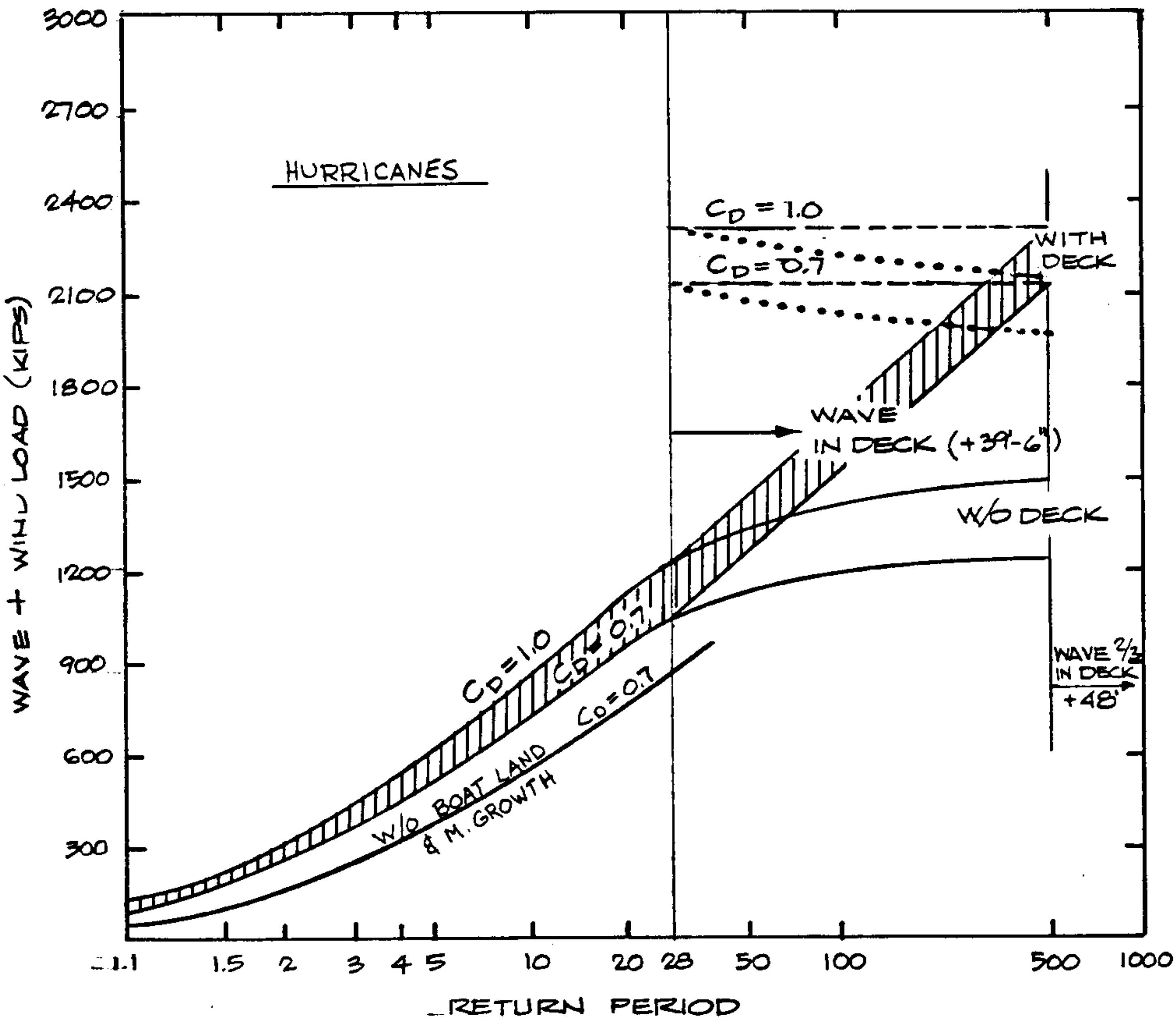
FIGURE 4-9



ENVIRONMENTAL FORCE VS. RETURN PERIOD - X-DIRECTION -

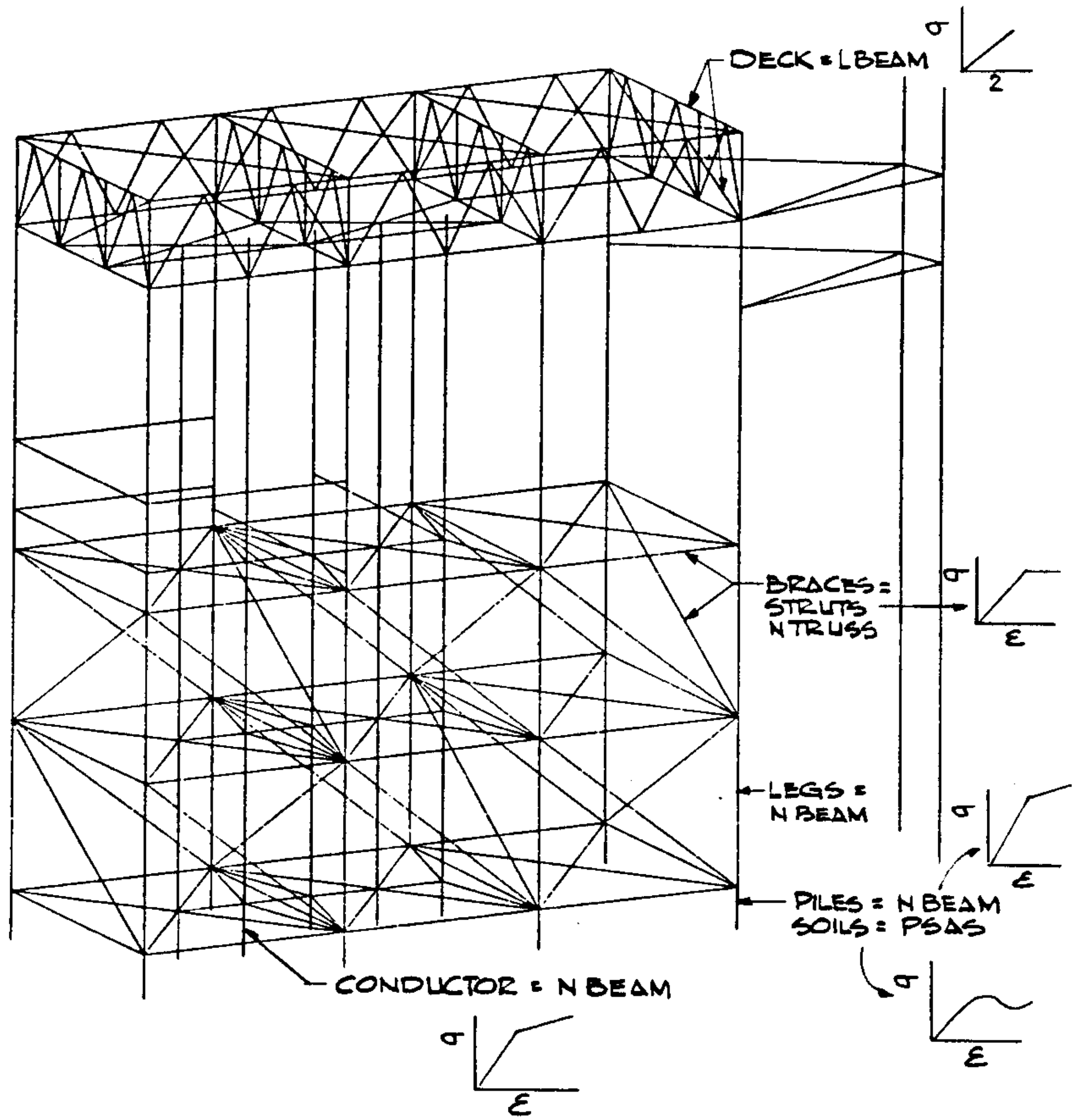
PLATFORM "B"

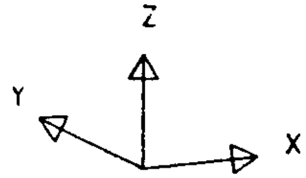
FIGURE 4-10



ENVIRONMENTAL FORCE VS. RETURN PERIOD - Y DIRECTION - PLATFORM "B"

FIGURE 4-11





NONLINEAR COMPUTER MODEL - PLATFORM "B"

FIGURE 4-12

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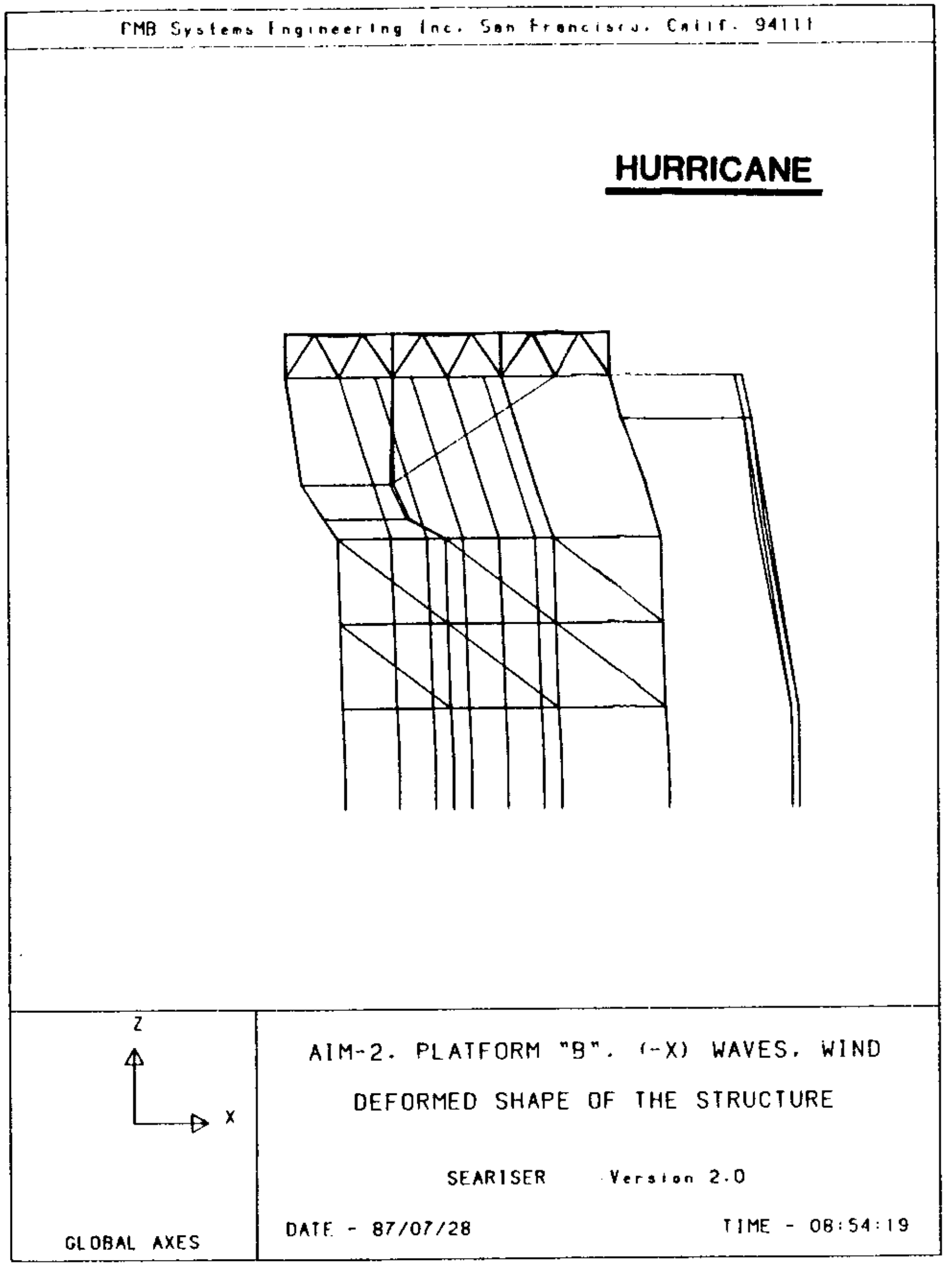
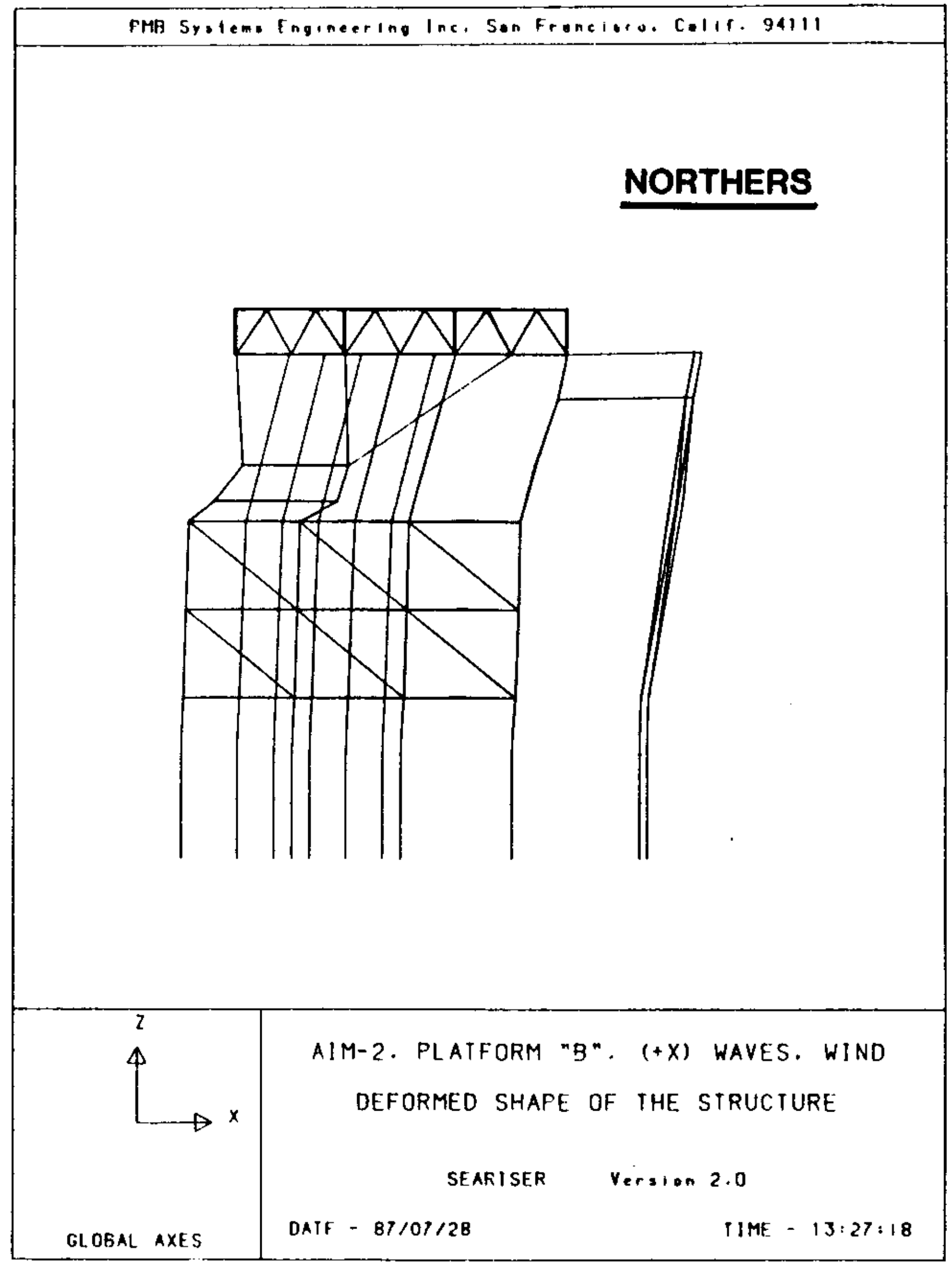
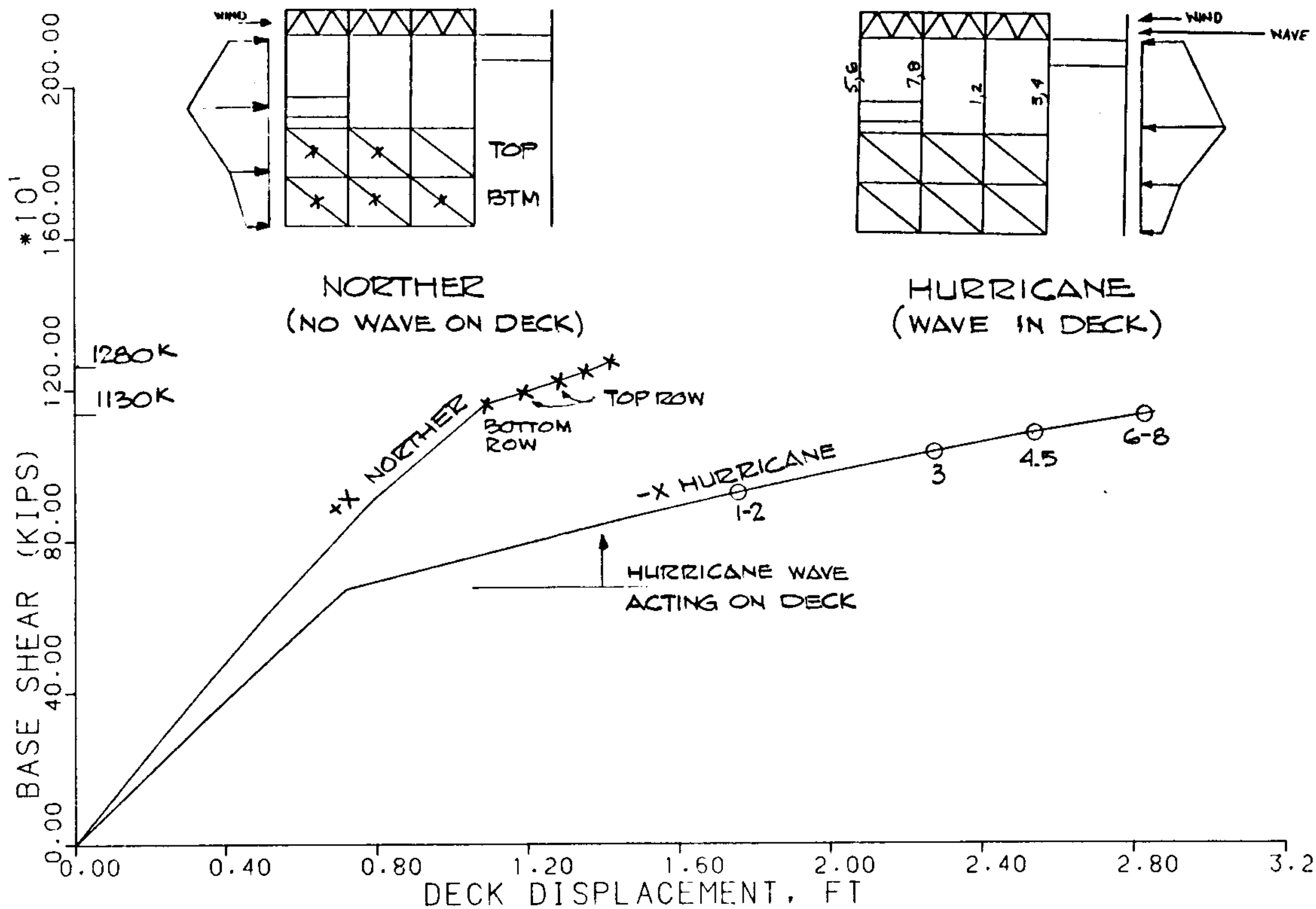




DEFORMED SHAPES - X DIRECTION - PLATFORM "B"

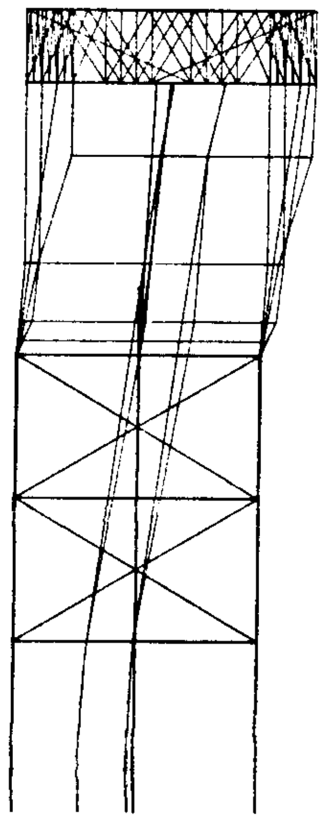
FIGURE 4-13

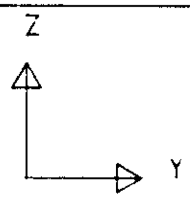


LOAD DISPLACEMENT CURVES - X DIRECTION - PLATFORM "B"

FIGURE 4-14

PMB Systems Engineering Inc, San Francisco, Calif. 94111





DEFORMED SHAPE - Y DIRECTION - PLATFORM "B"

FIGURE 4-15

SEARISER Version 2.0

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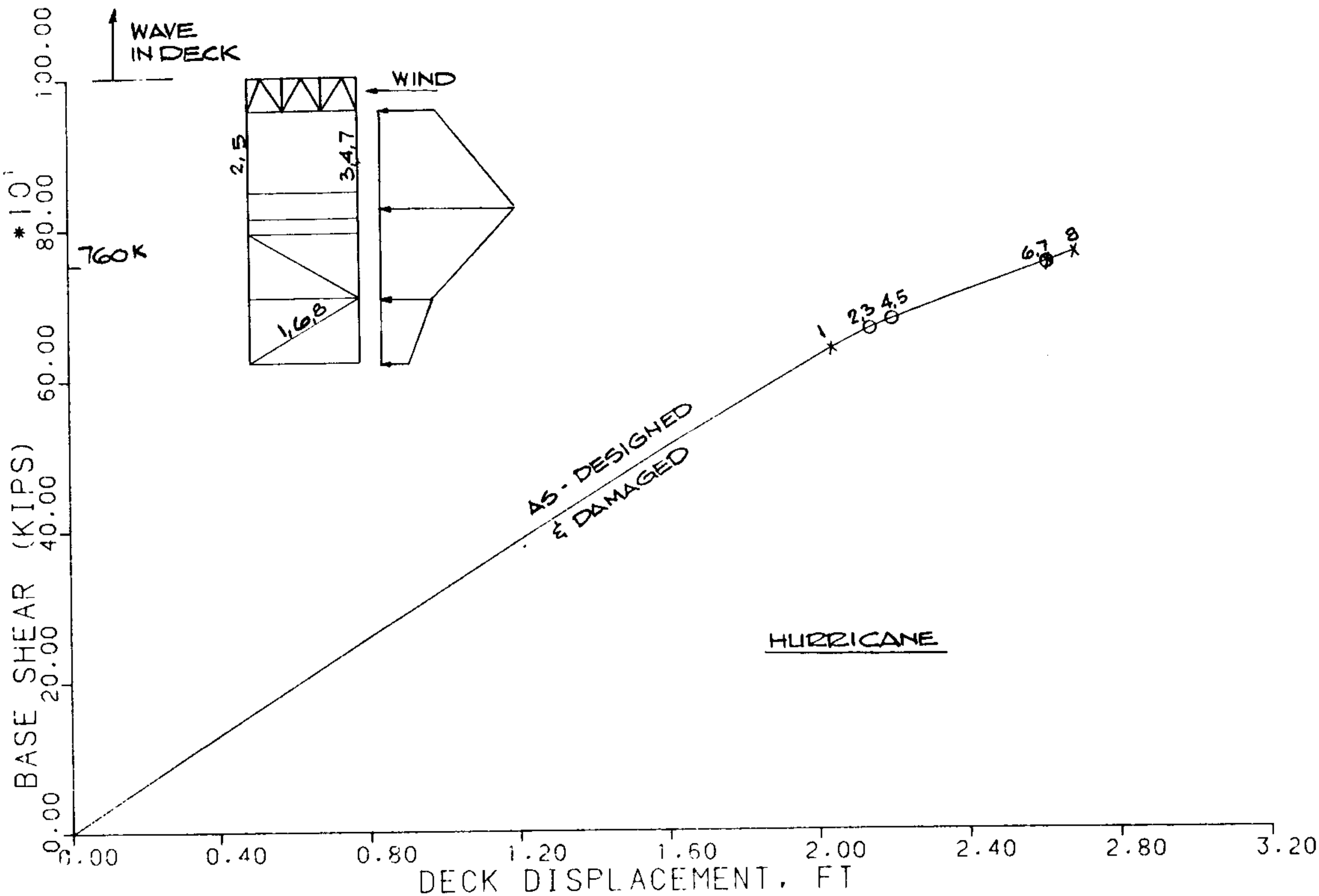
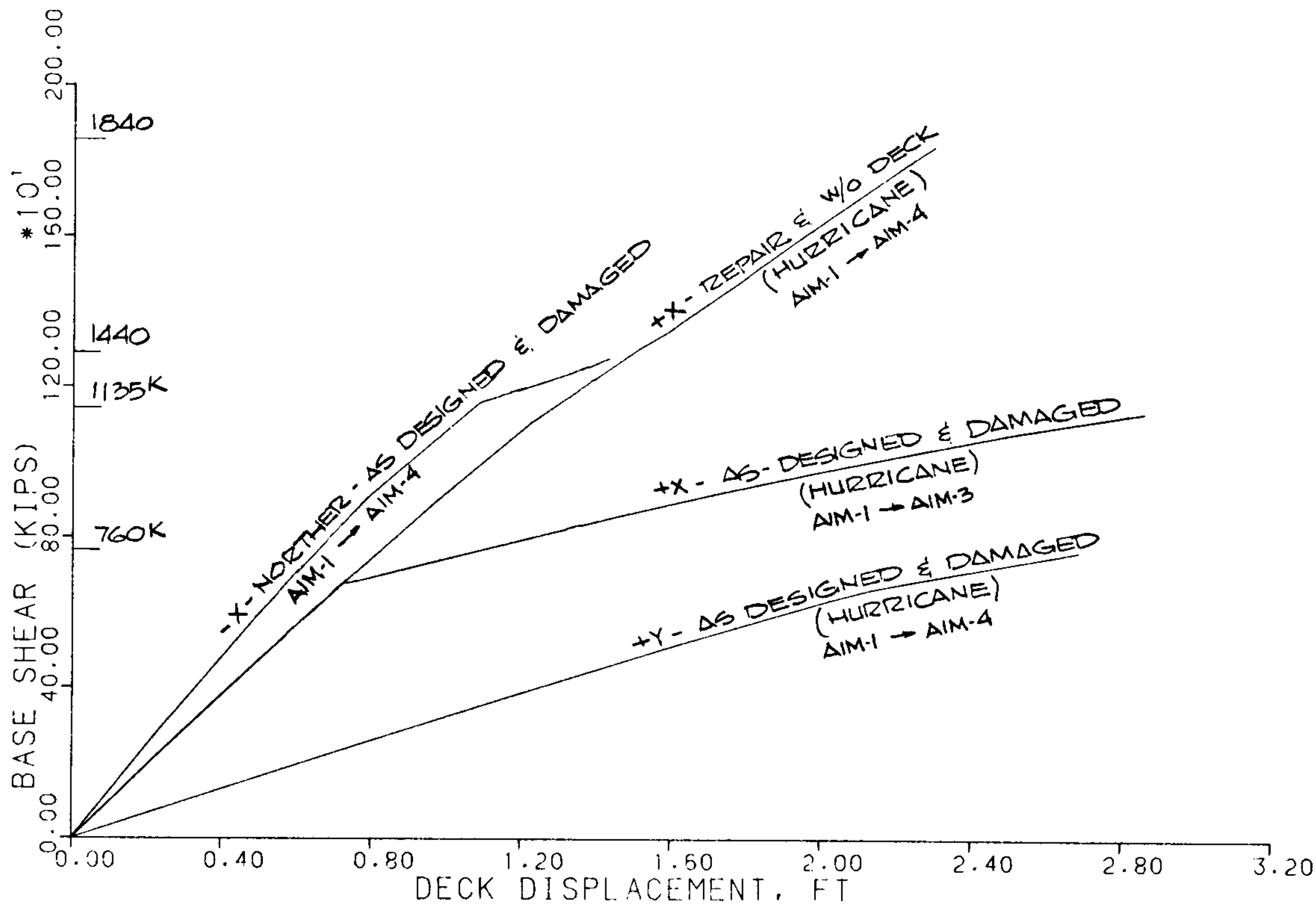


LOAD DISPLACEMENT CURVE - Y DIRECTION - PLATFORM "B"

FIGURE 4-16



LOAD DISPLACEMENT CURVES - AIM ALTERNATIVES - PLATFORM "B"

FIGURE 4-17

AIM Alternative 1	Cost	
Make No Repairs	$0.0 M	
2-Year Inspections (Moderate)	$0.05 M	
Engineering	$0.1 M	
	$0.15 M	Total Cost

AIM Alternative 2	Cost	
Remove Longitudinal Boat Landings	$0.02 M	
2-Year Marine Growth Removal	$0.18 M	
2-Year Inspections (Moderate)	$0.05 M	
Engineering	$0.1 M	
	$0.35 M	Total Cost

AIM Alternative 3	Cost	
Repair All Elements	$0.3 M	
2-Year Inspections (Moderate)	$0.05 M	
Engineering	$0.1 M	
	$0.45 M	Total Cost

AIM Alternative 4	Cost	
Repair All Elements	$0.3 M	
Raise Deck 5' (150 Yr. RP)	$1.0 M	
2-Year Inspections (Moderate)	$0.05 M	
Engineering	$0.1 M	
	$1.45 M	Total Cost

PROJECTED INITIAL COSTS OF AIM ALTERNATIVES - PLATFORM "B"

FIGURE 4-18

A. NET REVENUES

Equilibrate with Time

Net Cost =	$ 0.0

B. RESTORATION COSTS

Salvage	$ 500,000	
Plug and Abandon 5 Wells	500,000	(Mob/demob)
	1,000,000	P & A - 5 x $200,000/ea
TOTAL COST	$ 2,000,000	

C. REPLACEMENT COSTS

Jacket	300 T @ 1250	$ 375,000
Deck	500 T @ 1750	$ 875,000
Piling	500 T @ 750	$ 431,000
Equip	(w/o Quotes)	$ 1,160,000
Install	14 days @ 50,000	$ 700,000
Contingency	10 percent	$ 348,000
		$ 4,700,000
Redrill Wells	2.5M/ea x 5	$12,500,000
TOTAL COST		$17,200,000
TOTAL FUTURE COST		**$19,200,000**

PROJECTED FUTURE COSTS - PLATFORM "B"

FIGURE 4-19

$$E(C) = E(I) + E(F)$$

Conditions:

- 5-Year Remaining Life
- Platform Replacement
- $C_D = 0.7$
- Maximum Breaking Wave (46′) Return Period = 275 Yr.

Alternative 1: As-Is (AIM-1)			
E(I):	0.15 M		
E(F):	- Platform Capacity (Damaged Curve)		X = 1135 k Y = 760 k N = 1000+ k
	- Return Period		X = 115 Yr Y = 12 Yr N = 10000+ Yr
	- Cost = 3.3 + 26.9	=	19.2 M
E(C) =	0.15 + (1/12 - 1/275) x 19.2 x 5		
E(C) =	0.15 + 7.67	=	\$7.80 M

Alternative 2: Remove Boat Landings and Marine Growth (AIM 2)			
E(I):	0.35 M		
E(F):	- Platform Capacity	=	760 (Y)
	- Return Period	=	20 Yr (Y)
	- Cost	=	19.2 M
E(C) =	0.35 + (1/20 - 1/275) x 19.2 x 5		
E(C) =	0.35 + 4.45	=	\$4.80 M

AIM COST CALCULATION - PLATFORM "B"

FIGURE 4-20

$$E(C) = E(I) + E(F)$$

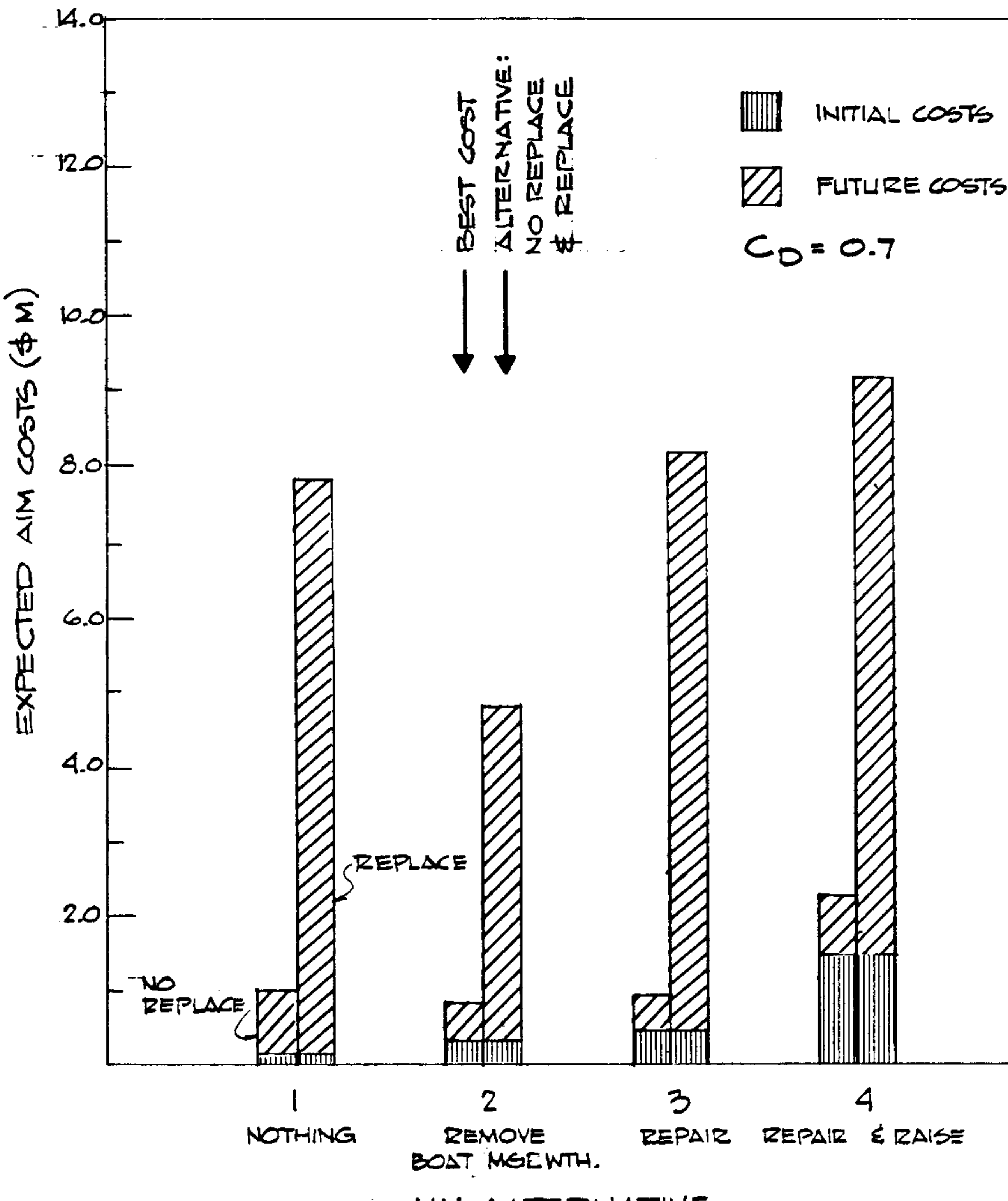
Alternative 3: Repair Elements (AIM 3)			
E(I):	0.45M		
E(F):	- Platform Capacity	=	760 k (Y)
	- Return Period	=	12 Yr (Y)
	- Cost	=	19.2 M
E(C) =	0.45 + (1/12 - 1/275) x 19.2 x 5		
E(C) =	0.45 + 7.67	=	8.12 M

Alternative 4: Repair and Raise Deck (AIM 4)			
E(I):	1.45 M		
E(F):	- Platform Capacity	=	760 k (Y)
	- Return Period	=	12 Yr (Y)
	- Cost	=	19.2 M
E(C) =	1.45 + (1/12 - 1/275) x 19.2 x 5		
E(C) =	1.45 + 7.67	=	9.12 M

AIM COST CALCULATION - PLATFORM "B"

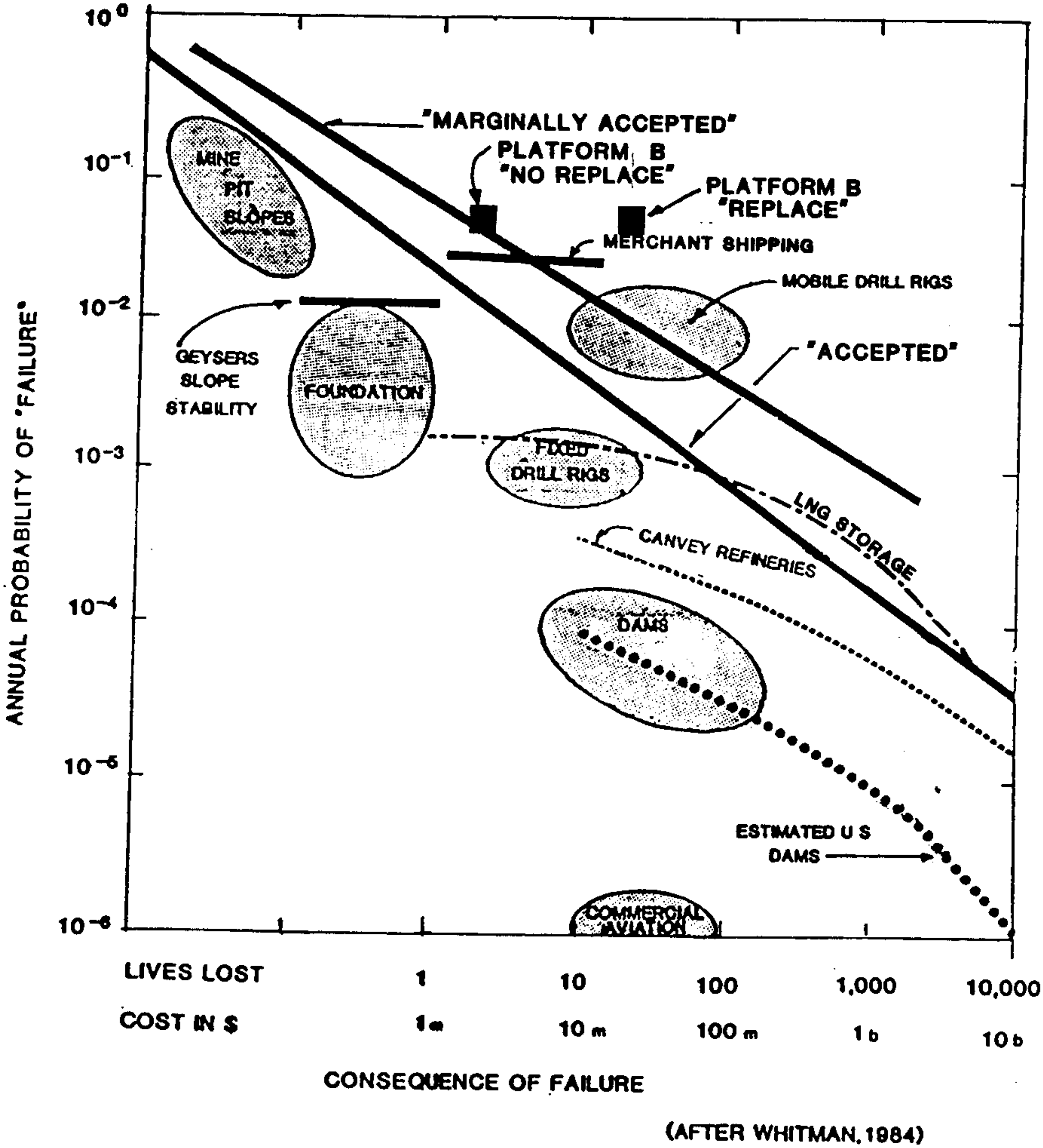
FIGURE 4-20

(Continued)



AIM COSTS - BAR CHART COMPARISON - PLATFORM "B"

FIGURE 4-21



HISTORICAL RISK DATA

FIGURE 4-22

5.0 SUMMARY

The AIM-II project has demonstrated application of the AIM-I approach to requalification of existing platforms. This demonstration involved AIM engineering analyses of two actual platforms provided by project participants. These platforms provided the study with a variety of realistic problems typically associated with older platforms.

The AIM-II demonstrations highlighted the key implementation problem areas. The first regarded engineering analyses of platform capacities or Ultimate Limit State resistances. The second regarded the processes for determining, justifying and communicating acceptability of a platform AIM program or suitability for service, with particular concerns for the public regulatory processes.

It is the authors' opinion that ample understanding and engineering technology exist to solve these two key problems. This understanding and technology need to be developed into a form suitable for routine industry and regulatory applications. Such efforts represent a developing maturation of the AIM approach, leading eventually to definitive engineering guidelines for the requalification of existing offshore platforms.

5.1 Platform "A"

Platform "A" is a five-leg tender drilling platform installed in 1963 in the central Gulf of Mexico in 140 feet of water. The structure supports nine gas wells, has a projected remaining economic life of 12 years, and is unmanned. Recent extensive condition inspections have disclosed a wide variety of damage and defects in the structure.

The ULS lateral load resistance of the platform in its as-is and as-installed conditions ranged from 950 to 1060 kips (Figures 3-16 and 3-17). These ULS resistances correspond to storm loadings having return periods in the range of 30 to 50 years (Figure 3-10), implying risk rates in the range of 2 to 3 percent per year.

Platform "A" successfully withstood Hurricane "Hilda" shortly after its installation (1964). This storm should have produced wave crests that reached the lower decks, yet the platform survived without any apparent damage, indicating a "proof" loading in the range of 1200 to 1400 kips (Figure 3-10) and a risk rate of less than 1 to 2 percent per year.

Options to maintain and modify the platform were evaluated, including leg-joint grouting and deck raising. For the condition of non-replacement of the structure in the event of a failure (e.g. failure occurs late in the 12-year life), the most attractive AIM alternative from a commercial cost-benefit standpoint is to maintain the platform in its as-is (damaged) state, performing extensive condition surveys/inspections on a two-year frequency to assure that there are no further changes in the structure's condition.

From a standard of practice (historical) valuation standpoint, this option does not apparently meet minimum requirements. The platform meets requirements if the Hurricane Hilda experience is allowed to determine the risk rate.

Only in the case of raising the deck and making all repairs does the risk-consequence combination obviously meet the standard of practice (historical) guidelines defined in Section 3.5.2. This option would only be justified from a commercial standpoint if the gas reserves and income would justify replacement of the facilities in the event of a failure. Given that the net value of the facility is about $95 million (Appendix D) and the initial cost of the repairs and raising the deck is $2.7 millions, the AIM option investment of 3 percent of the facility's value would appear justified.

5.2 Platform "B"

Platform "B" is an eight-leg tender drilling platform installed in 1959 in the central Gulf of Mexico in 52 feet of water. The structure supports seven oil wells, has a projected useful economic life of 5 years, and is unmanned. Recent condition surveys have disclosed a limited amount of damage to the structure.

The ULS lateral load resistance of the platform in its as-is and as-installed conditions range from 1135 kips (end-on wave approach) to 760 kips (broadside wave approach). These ULS resistances correspond to storm loadings having return periods in the range of 20 to 100 years (Figure 4-10), implying risk rates in the range of 1 to 3 percent per year.

Platform "B" successfully withstood hurricanes Carla (1961) and Alicia (1985) (Figure 4-4). These storms produced near-breaking wave heights and crest elevations that should have reached the lower deck (Figure 4-5). This experience would indicate platform risk rates of less than about one percent per year (Figure 4-10).

Options to maintain and modify the platform were evaluated, including repairs, raising the decks, and reducing the wave loadings (boat landing and marine growth removal). Based on a commercial cost-benefit assessment, the most attractive AIM option was that of wave load management (for both replacement and nonreplacement scenarios). The net value of the facility compared with the initial AIM cost would apparently justify the investment.

From a standard of practice (historical) valuation standpoint, the most commercially attractive AIM option apparently does not meet minimum requirements. The combination of risk (5 percent per year) and consequences ($20 to $30 million) exceeds marginally acceptable levels. The platform meets these requirements if the hurricane Carla and Alicia experience is allowed to determine the risk rate (less than one percent per year).

Recognizing the low probability of experiencing maximum storm loadings acting broadside to the platform (from east or west) in the very shallow water, the best estimate platform capacity is likely of the order of 1100 to 1200 kips (end-on), implying risk rates in the range of two percent per year. These rates would fall in the marginally acceptable range (Figure 4-22).

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APPENDIX A

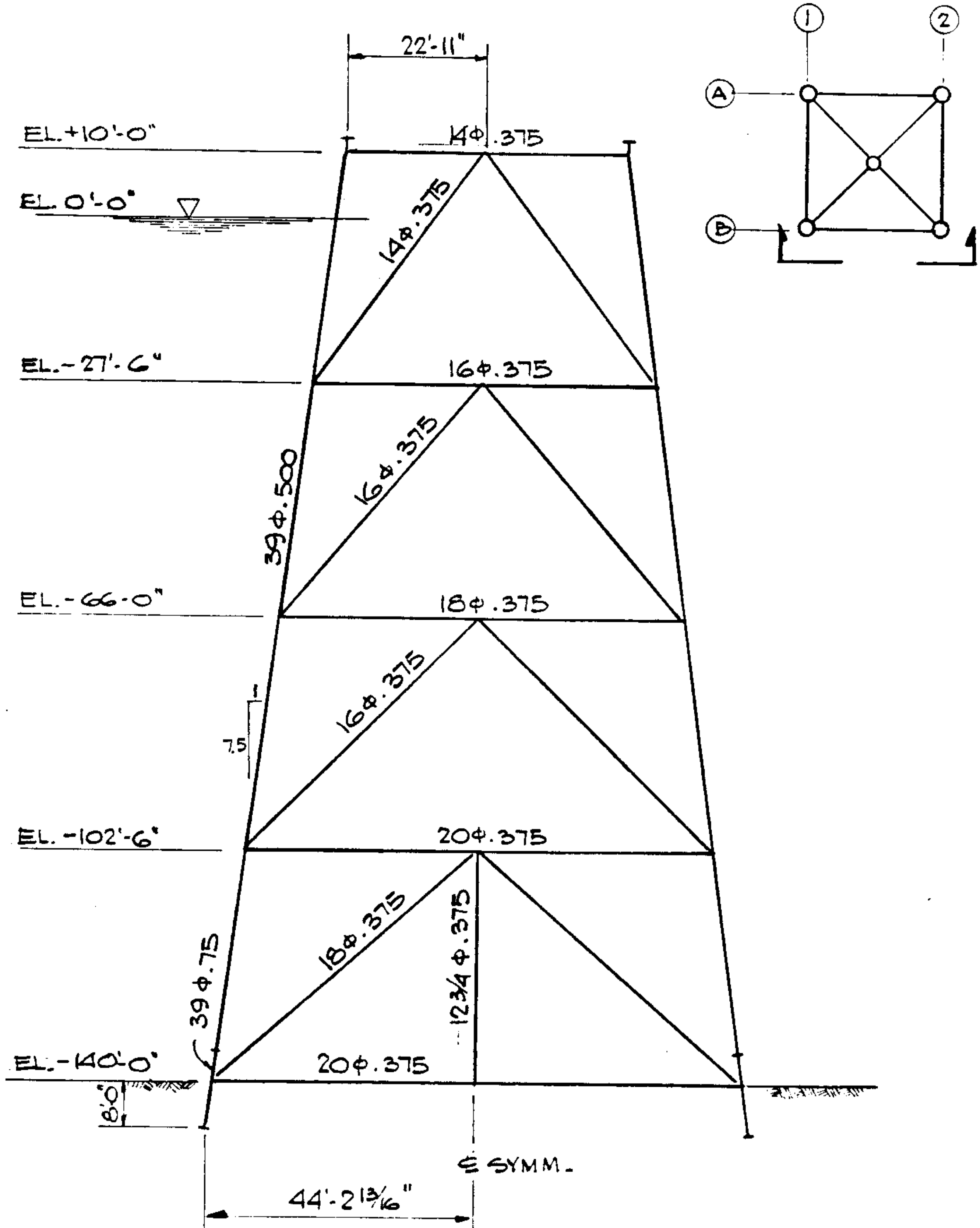
PLATFORM "A" EVALUATION

APPENDIX A

PLATFORM "A" EVALUATION

Page	Description
A.1 - A.4	Typical member sizes. Note interior vertical diagonals page A.2.
A.5 - A.9	Detailed platform background information.
A.10	Damage Report Summary.
A.11 - A.12	Location of damaged members.
A.13 - A.16	General views of three-dimensional computer model.
A.17 - A.19	Storm surge, wind speed and current speed return period information. These conditions are assumed to coexist with the wave of same return period. The plateaus indicate maximum possible for Gulf.
A.20	Wave profile for wave just under deck. Wave steepness = 1/12 (height to length).
A.21	Wave horizontal water particle velocities for selected return periods.
A.22	Wave pressure distribution for wave just under deck.
A.23	Wave force time history with and without the deck. Note the "jump" of almost 800 kips for the wave in the deck. See Section 3.3 for further discussion.
A.24	PSAS single pile model. PSAS models were developed for all piles and conductors and included in the 3-D platform model.
A.25	Soil and pile data used for PSAS analysis.
A.26 - A.27	Comparison of detailed and coarse single pile models for lateral and axial directions. The detailed model had 20 elements. The coarse model had 8 elements. The coarse model (with fewer elements) was the one eventually installed in the 3-D platform model. The comparison is required to ensure the coarse model adequately models the soil-pile interaction.

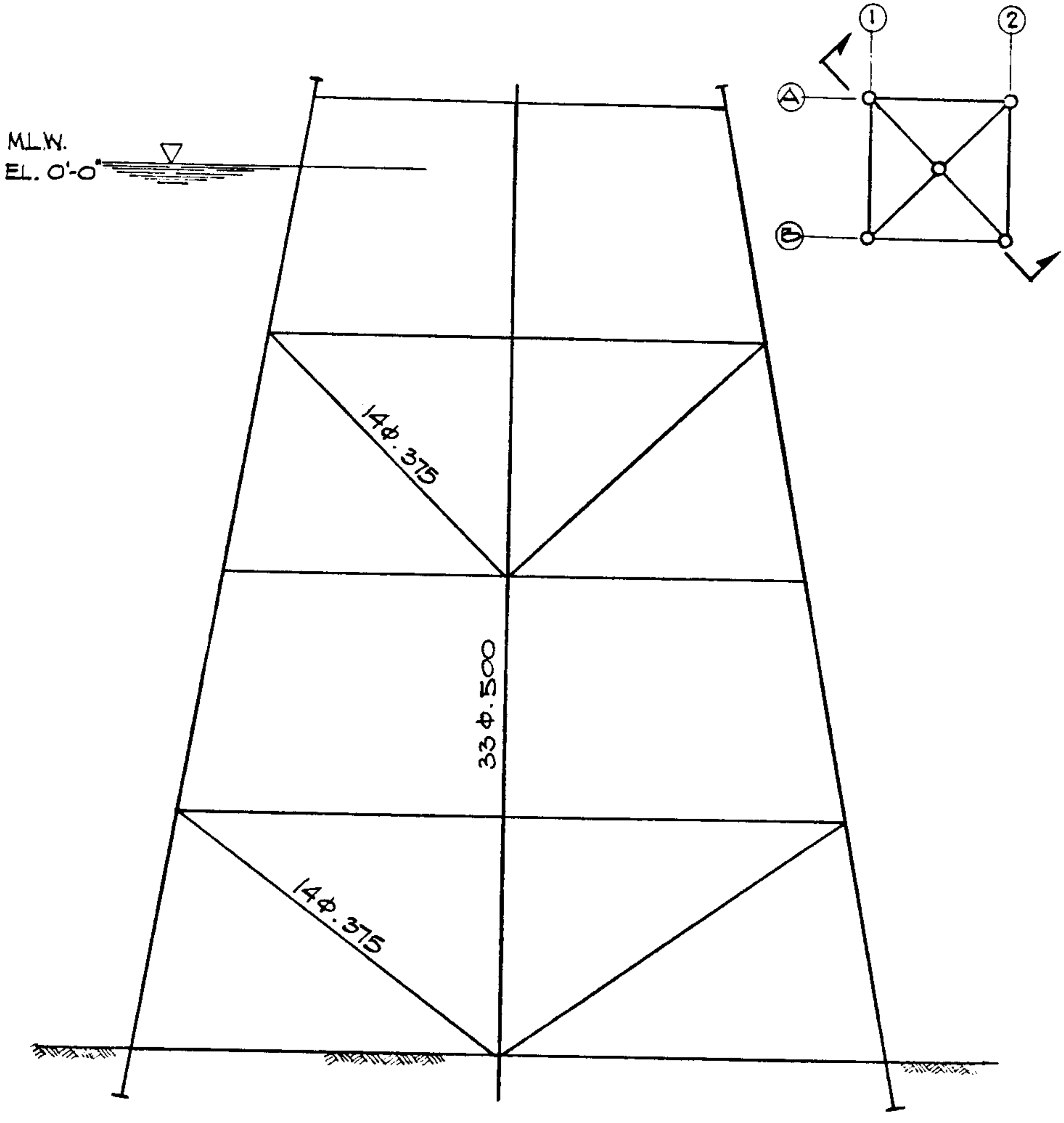
A.28 Pile top (mudline) horizontal displacement during ultimate capacity analysis.



ROWS A&B, 1&2

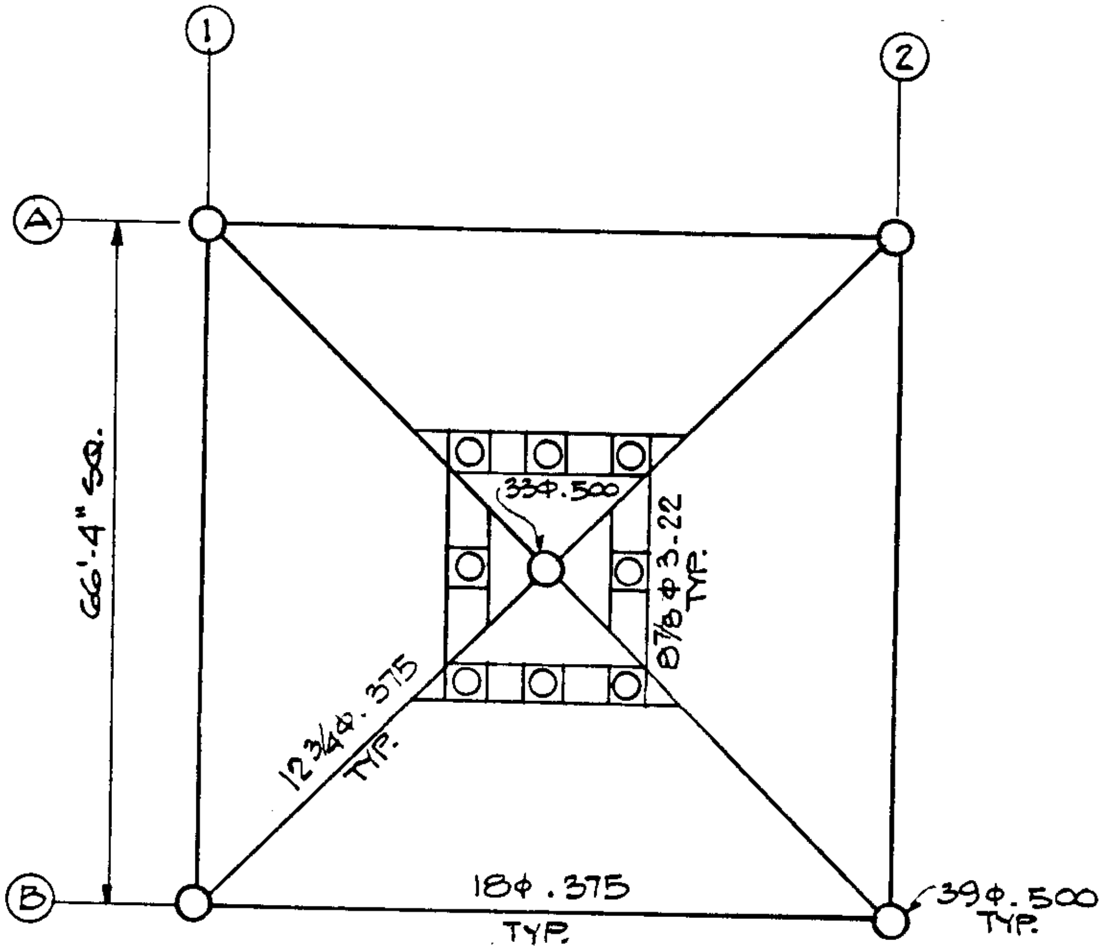
JACKET ELEVATION

PLATFORM A



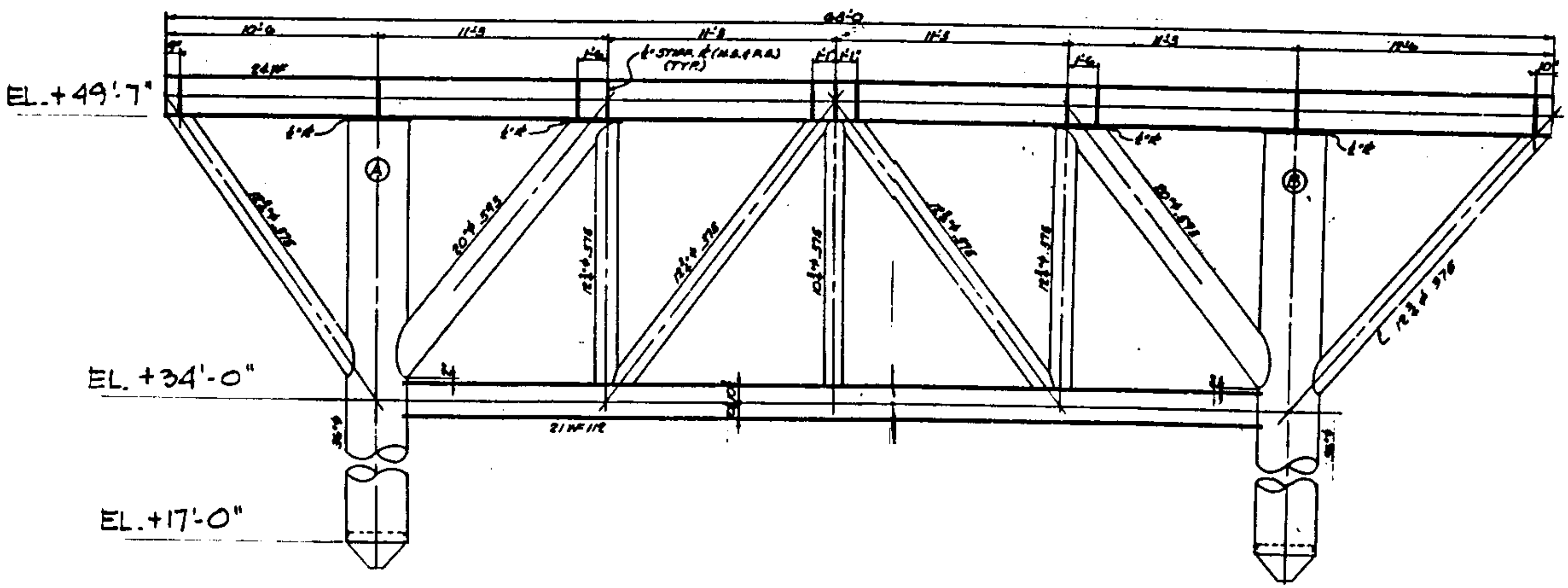
DIAGONAL JACKET ELEVATION

PLATFORM A



PLAN @ELEV. -65'-0"

(TYP, THROUGHOUT JACKET)



DECK TRUSSES

PLATFORM "A"

I. VITAL STATISTICS

A. Property Information

Location: Central Gulf of Mexico

Water Depth: 140 Feet MLW

Installed: 1963

Number of Legs: 5 With a Center Leg (Pile/Conductor)

Number of Jacket Elevations: 5

Top of Jacket Dimensions: 45 by 45 Feet

Leg Batter: 1/7.5

Number of Wells:

9 Design and 9 Presently (5 Are Producing)

8 at 20" ø, Plus Center Pile/Conductor at 30" ø

Location of Wells: Center of Jacket

Type of Platform: Tender Drilling and Production Platform

Number of Boat Landings: 2

Number of Barge Bumpers: 4

Piles Grouted: No

Pile Diameter:

4 - Outer - 36 Inches

1 - Center - 30 Inches (Pile/Conductor)

Pile Penetration: 170 ft.

Number of Risers: 2

Type of Cathodic Protection System: Sacrificial Anodes

(more added in 1986)

Elevation of Top of Jacket: +10 Feet

Number of Deck Levels: 2

Elevation of Cellar Deck: +34 Feet

Elevation of Top Deck: +52 Feet

Elevation of Sump Deck: +25.5 Feet

Plan Dimension of Decks: 60 by 60 Feet

Deck Covering: Grating

B. Personnel Information

Quarters: No - Unmanned

Helideck: Yes

C. Production Information

Production Equipment: Manifold, Test Separator, Launcher Located on Cellar Deck

Production: Natural Gas

D. Environmental Impact Information

Pertinent Data: None

E. Risk Potential Information

Expected Future Life: 12 Years

II. VITAL STATISTICS

A. Design Information

Soil Boring: Yes

Environmental Report: No

Design Specification: No

Design Report: No

Construction Drawings: Yes

B. Construction Information

Fabrication Date: 1962 - 1963

Fabrication Specification: No

Primary Materials Used: Mild Steel (A36)

Joint Material: Mild Steel (A36)

Fabrication Inspection Records: No

Splashzone Material: Wrap and Paint

Paint System: Two Coat

Installation: Derrick Barge

Piles to Grade? Apparently

Driving Records: No

C. Operational Information

Drilling Phase: 1963-1964

Structural Modifications During Drilling: None Known

Incidents During Drilling: Lots of Debris at Mudline

Production Phase: 1964 to Present

Well Workover: Yes, with Drilling Tender as Recently as 1985.

Known Incidents During This Phase: Sump Pump at Top of Jacket Continuously Sprayed Water onto Jacket Leg, Thereby Corroding It Away. Leg Joint Was Replaced with New Material

D. Accident Information

Boat Collision: Drilling Tender Tied Off to Platform

Dropped Objects: Debris on Subsea Jacket Braces

Fires or Explosions: None Known

E. Maintenance and Present Status

Summary of Inspections: 1981 and 1986

Discoveries Above Water: Yes Both Times

Discoveries Below Water: Yes Both Times

List of Structural Defects:

Diagonal Brace Missing from -28 to -65

Cracked Horizontals at -28: 3

Cracked Diagonals Between -28 and -65: 1

Broken Diagonals Between -28 and -65: 2

Broken Diagonals Between -65 and -102: 1

Cracked Horizontals at -65: 3

Status of Cathodic Protection System: Initial System Depleted, Retrofitted Systems Done Twice

Status of Above Water Paint System: Areas of Corrosion

Present Marine Growth: 2.5 Inches from Waterline to -28; Tapers off Below -28 to Mudline

Scour at Base: Seven Feet of Deposit Seen in 1981; Four Feet of Scour Seen in 1986

History of Structural Repairs: Done in 1986

Missing Diagonal Brace from -28 to -65

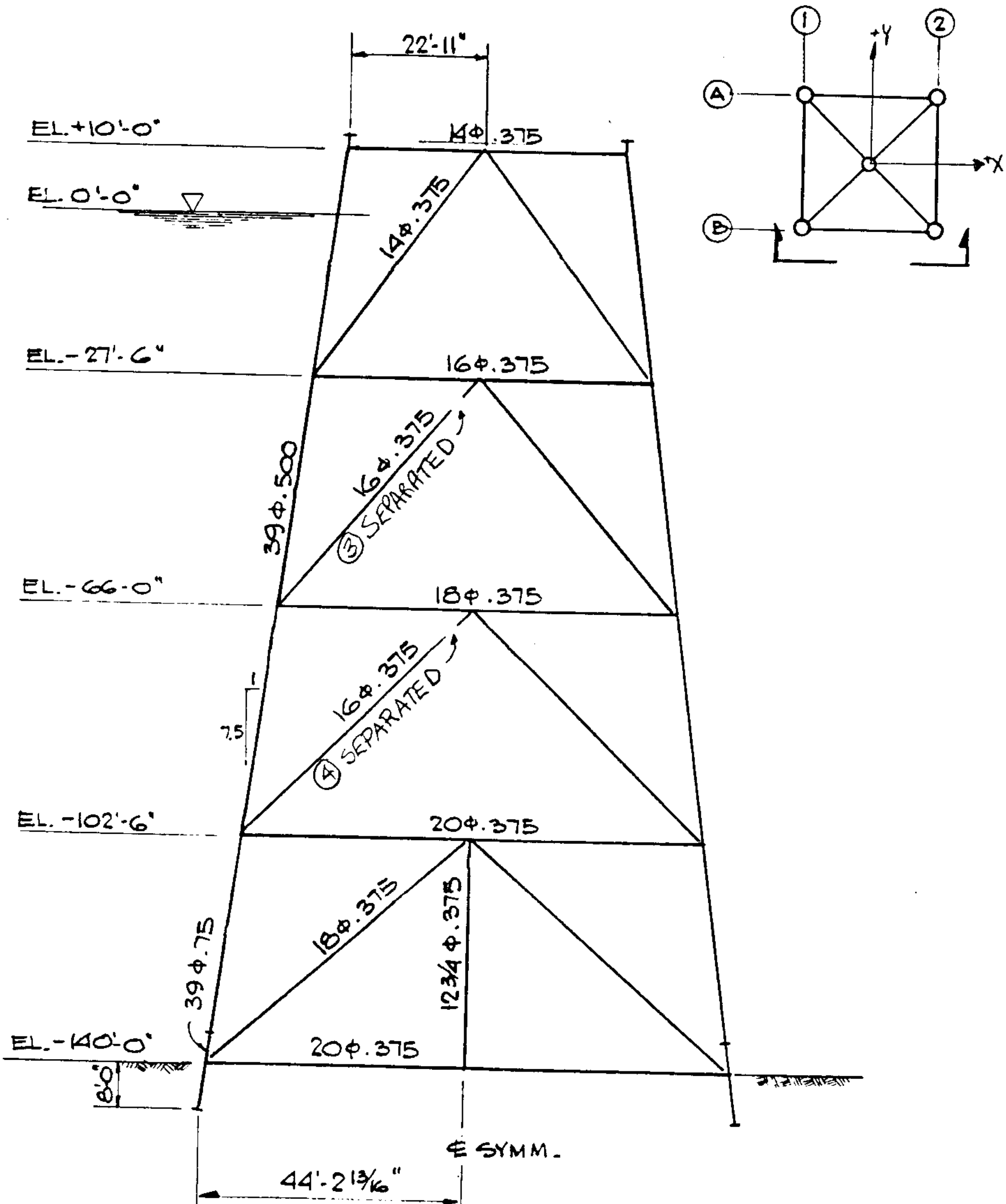
Broken Diagonals Between -28 and -65

Broken Diagonals Between -65 and -102

PLATFORM "A"

DAMAGE REPORT SUMMARY

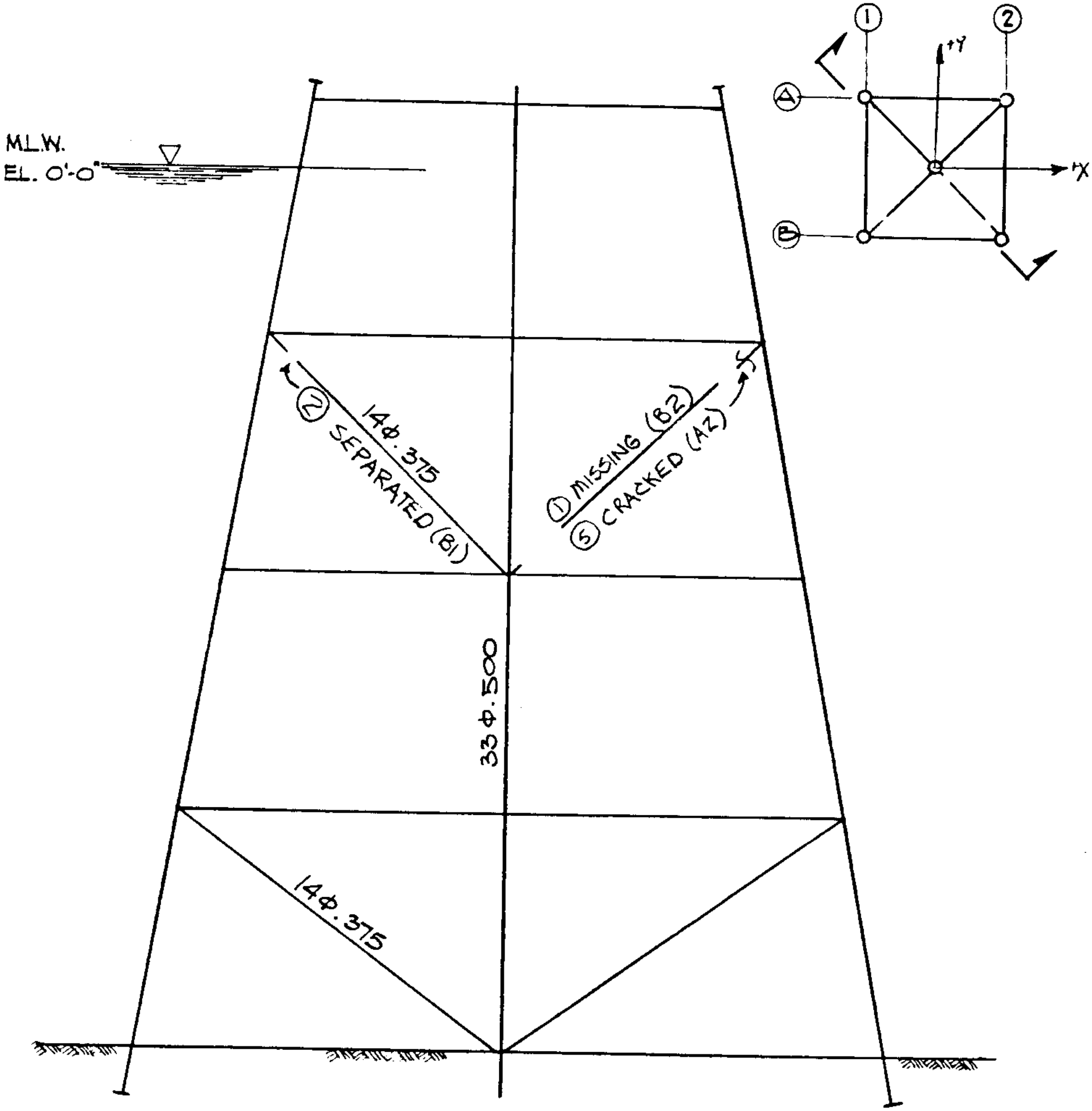
ITEM NO.	LOCATION	DAMAGE
1	Vertical Interior Diagonal B2 at -27.5′ to Center Leg at -65′	Missing
2	Vertical Interior Diagonal B1 at -27.5′ to Center Leg at -65′	Completely Separated from Leg at B1
3	Vertical Face Diagonal, Row B Midpoint B1 to B2 at -27.5′ to B1 at -65′	Completely Separated from Horizontal Member B1 to B2 at -27.5′
4	Vertical Face Diagonal, Row B Midpoint B1 to B2 at -65′ to B1 at -102.5′	Completely Separated from Horizontal Member B1 to B2 at -65′
5	Vertical Interior Diagonal A2 at -27.5′ to Center Leg at -65′	Cracked at A2 from 12:00 to 5:00 Crack Length = 40"
6	Horizontal Interior Diagonal -65′ B2 to Center Leg	Cracked at B2 from 9:30 to 2:30 Crack Length = 14"
7	Horizontal Interior Diagonal -28′ B2 to Center Leg	Cracked at B2 from 4:00 to 8:30 Crack Length = 12.75"
8	Horizontal Interior Diagonal -28" A2 to Center Leg	Cracked at A2 at 4:30 Crack Length = 12.5"
9	Horizontal Face Member Row B B1 to B2 at -65′	Cracked at B2 at 3:00, 5:00, 9:00 Crack Length = 7.25" Total



ROWS A&B, 1&2

JACKET ELEVATION

PLATFORM A

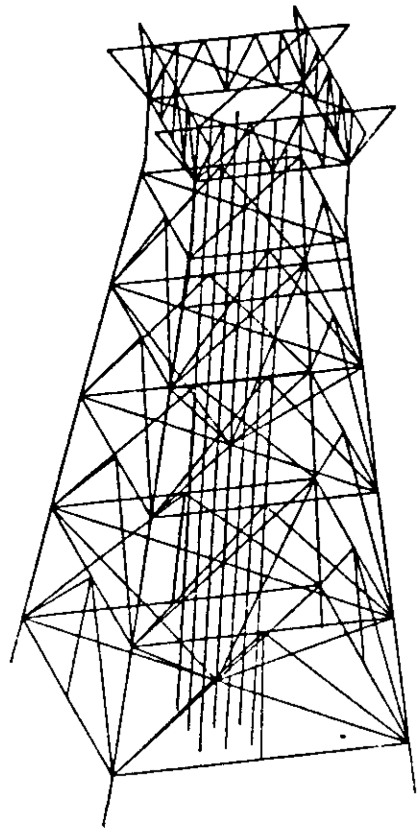


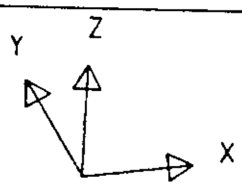
(6)-(9) MISC. HORIZ. MEMBER CRACKS

DIAGONAL JACKET ELEVATION

PLATFORM A

PMB Systems Engineering Inc. San Francisco. Calif. 94111





GLOBAL AXES

140'W/D PLATFORM "A"

GENERAL VIEW OF THE STRUCTURE

SEARISER Version 2.0

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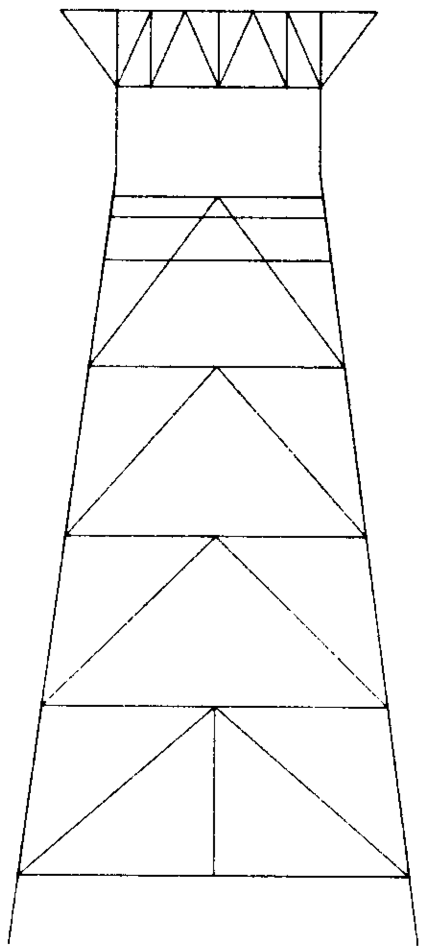

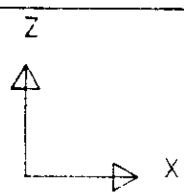

GLOBAL AXES

140'W/D PLATFORM "A"

ROW "A" ("B") FACE

SEARISER Version 2.0

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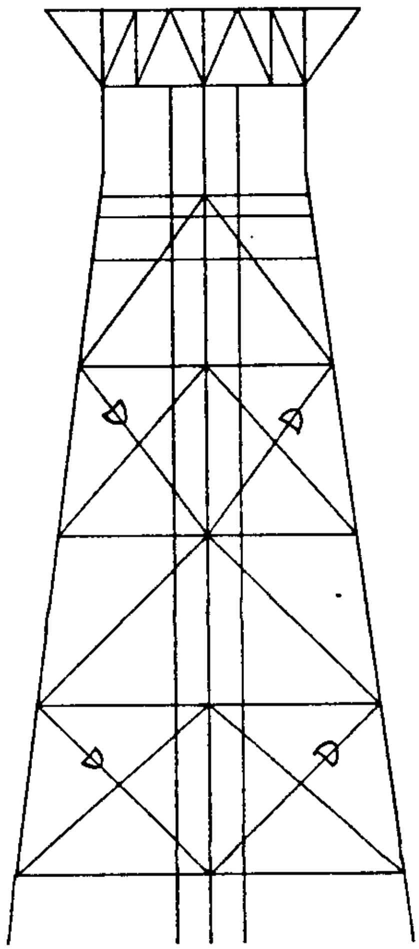
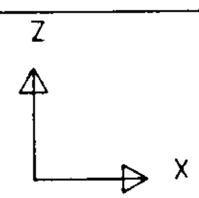
TIME - 16:27:13

PMB Systems Engineering Inc. San Francisco, Calif. 94111



D = VERTICAL INTERIOR DIAGONALS



GLOBAL AXES

140' W/D PLATFORM "A"

SOUTH TO NORTH VIEW OF THE STRUCTURE

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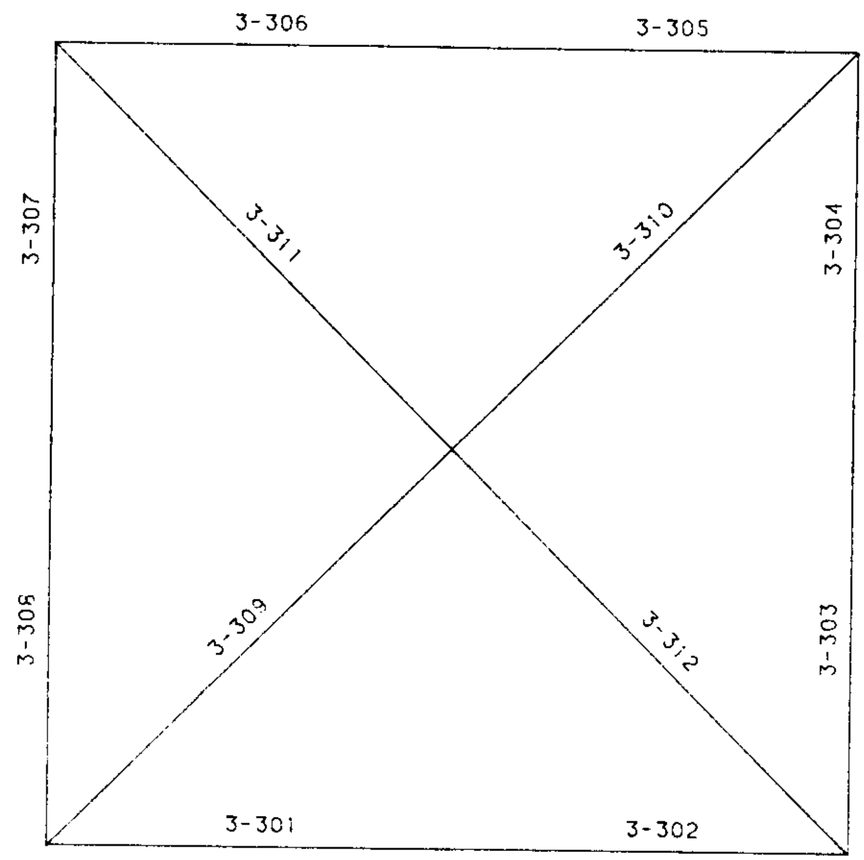

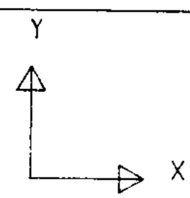

140'W/D PLATFORM "A"

PLAN AT ELEVATION +10.0 FT

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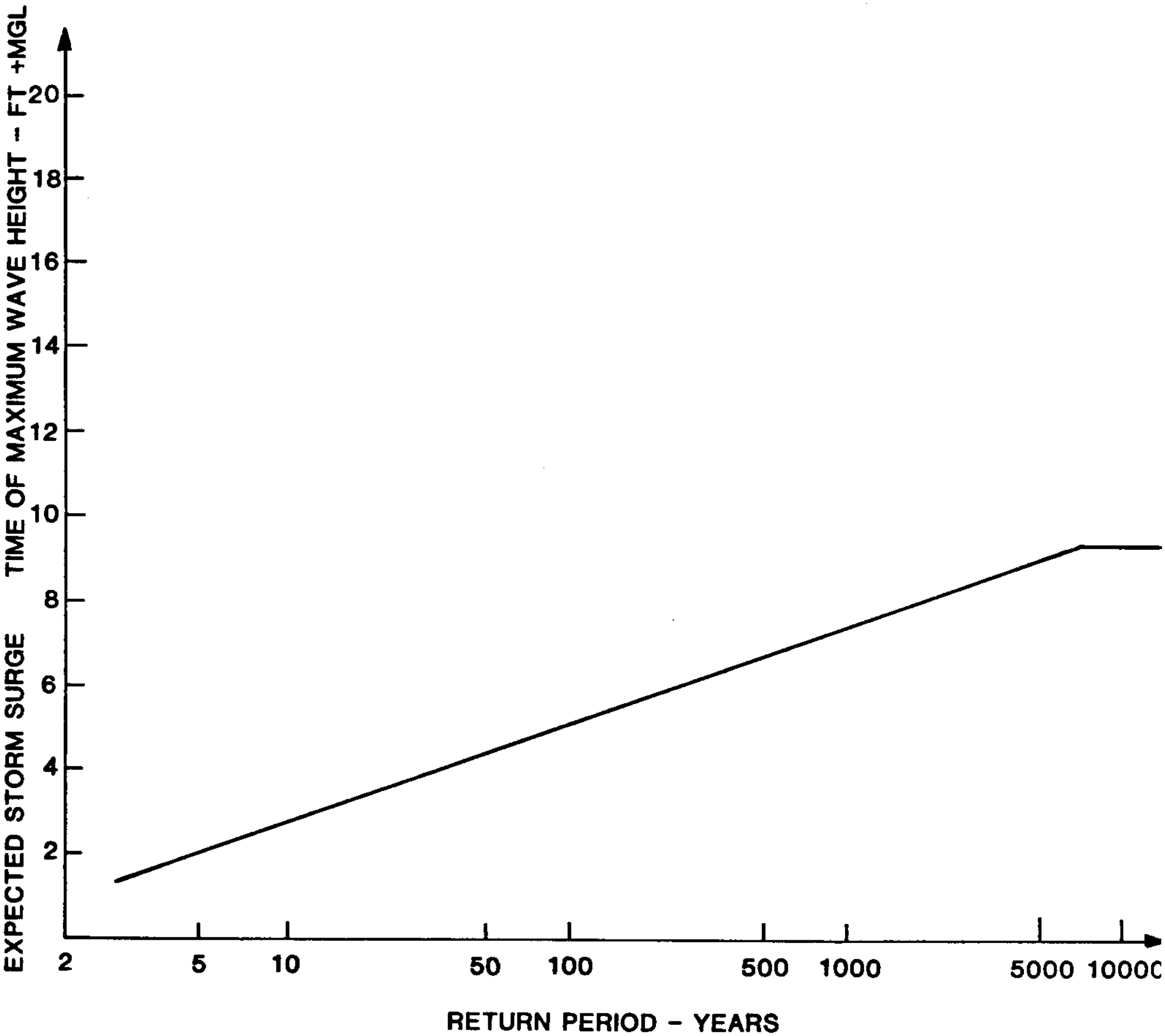
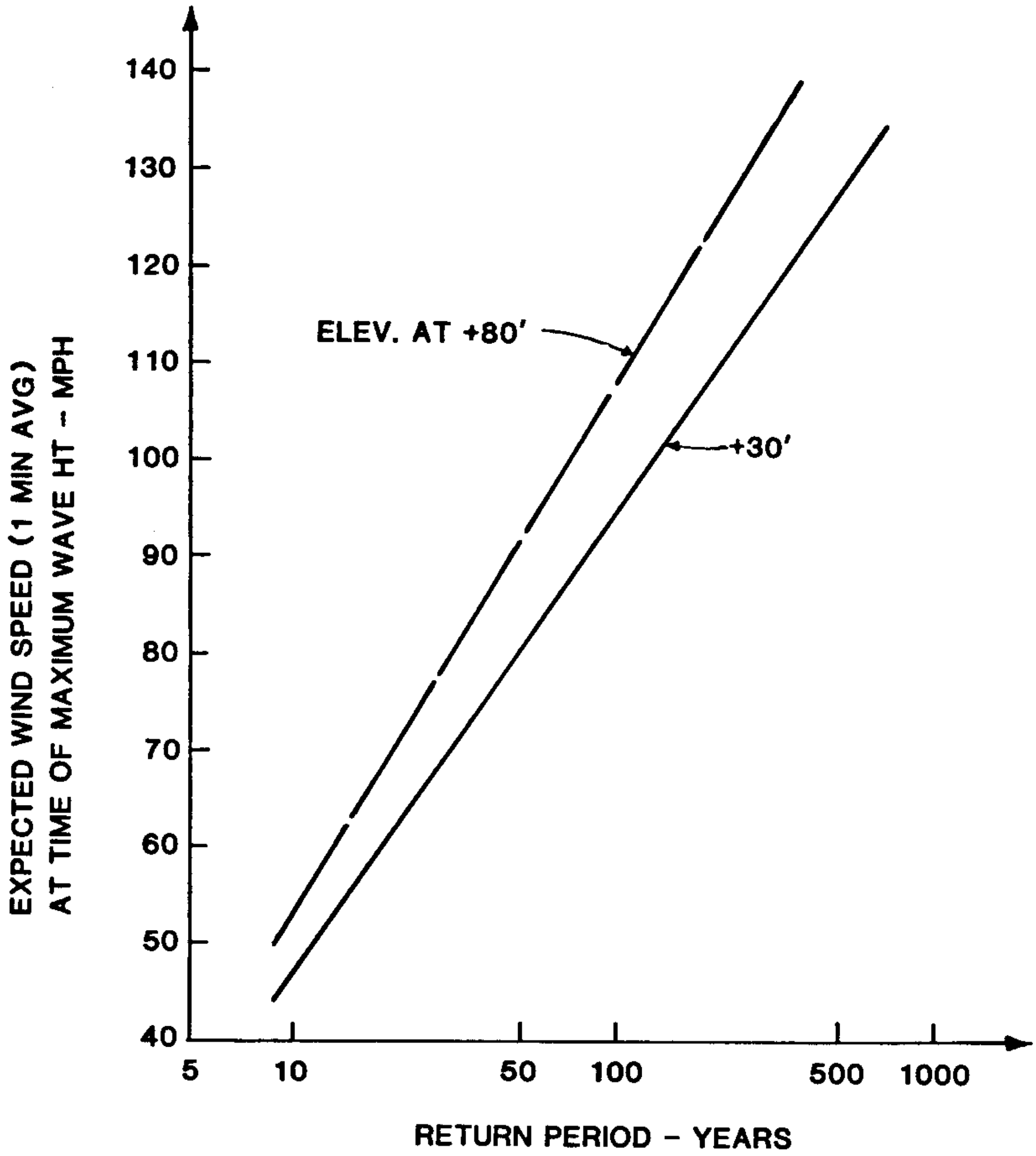
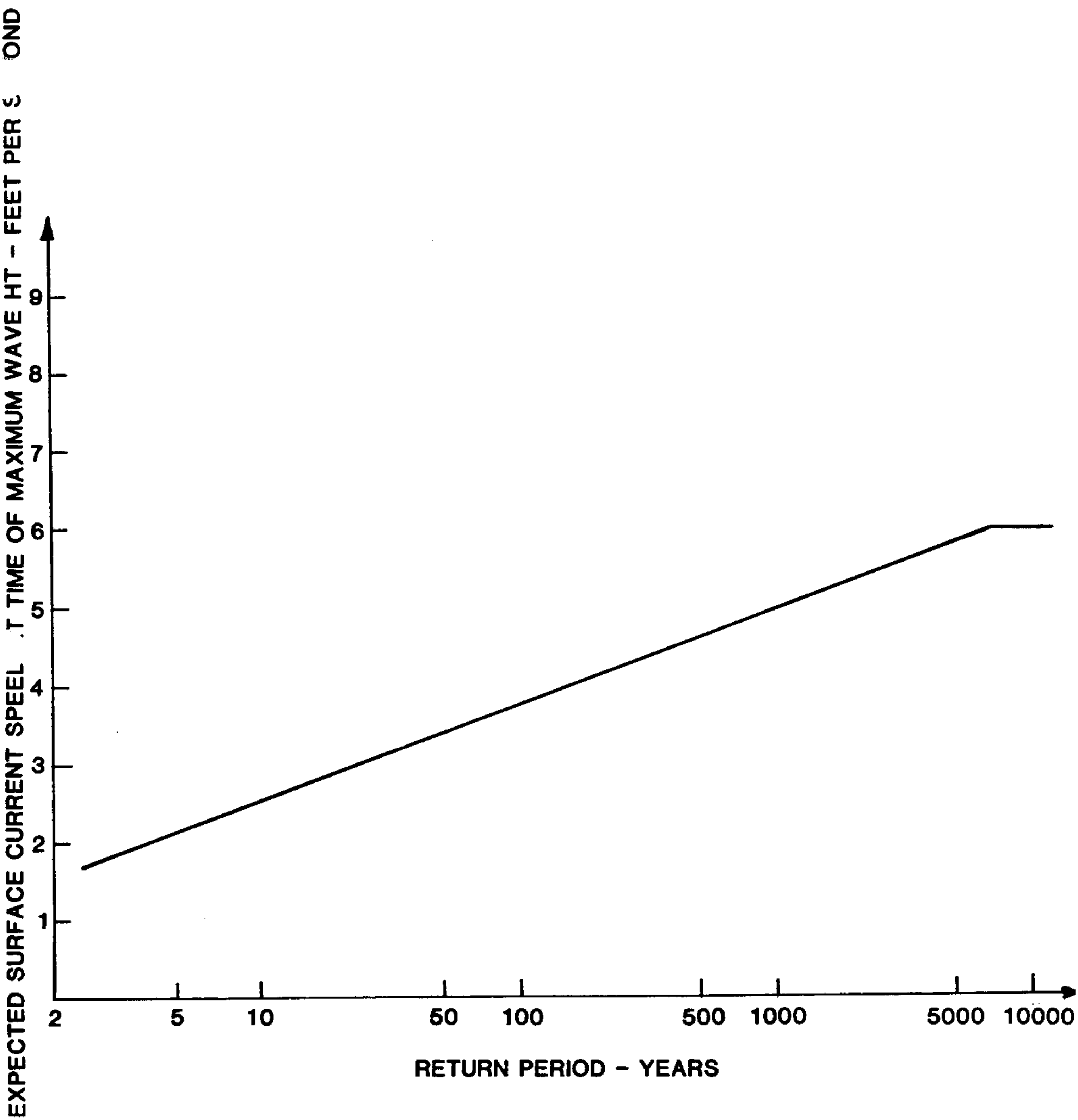


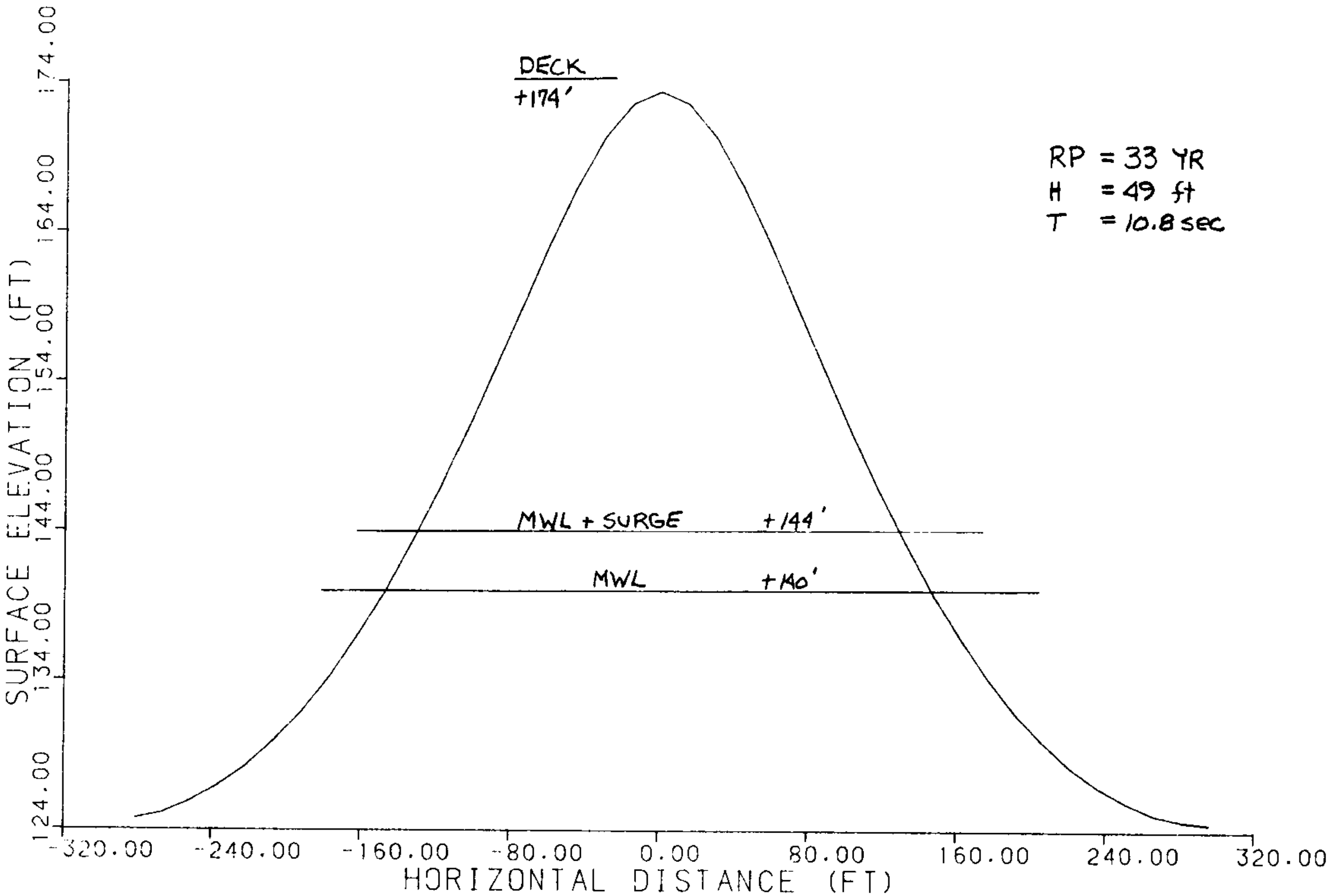
STORM SURGE VS. RETURN PERIOD - PLATFORM "A"



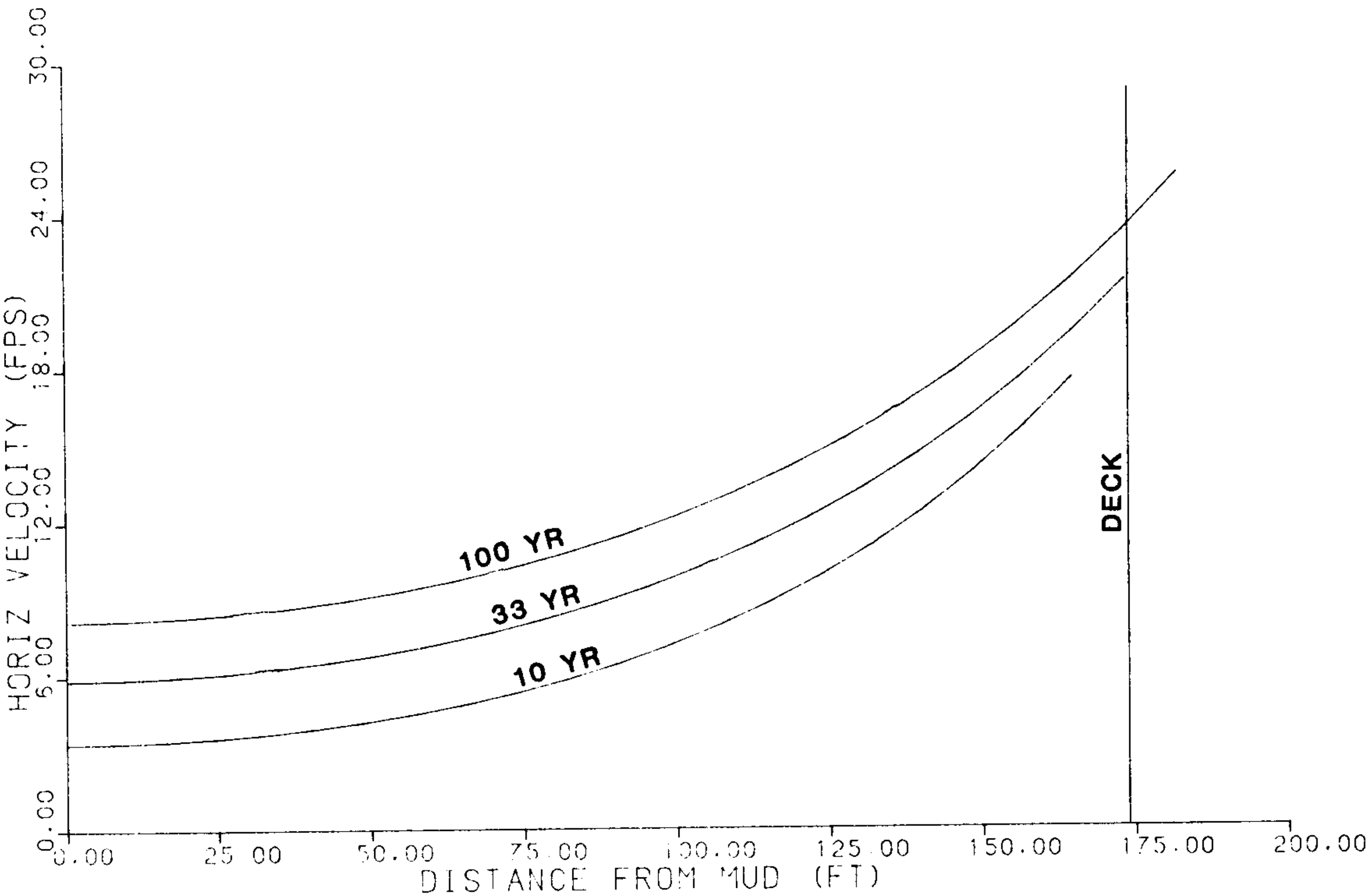
WIND SPEED VS. RETURN PERIOD - PLATFORM "A"



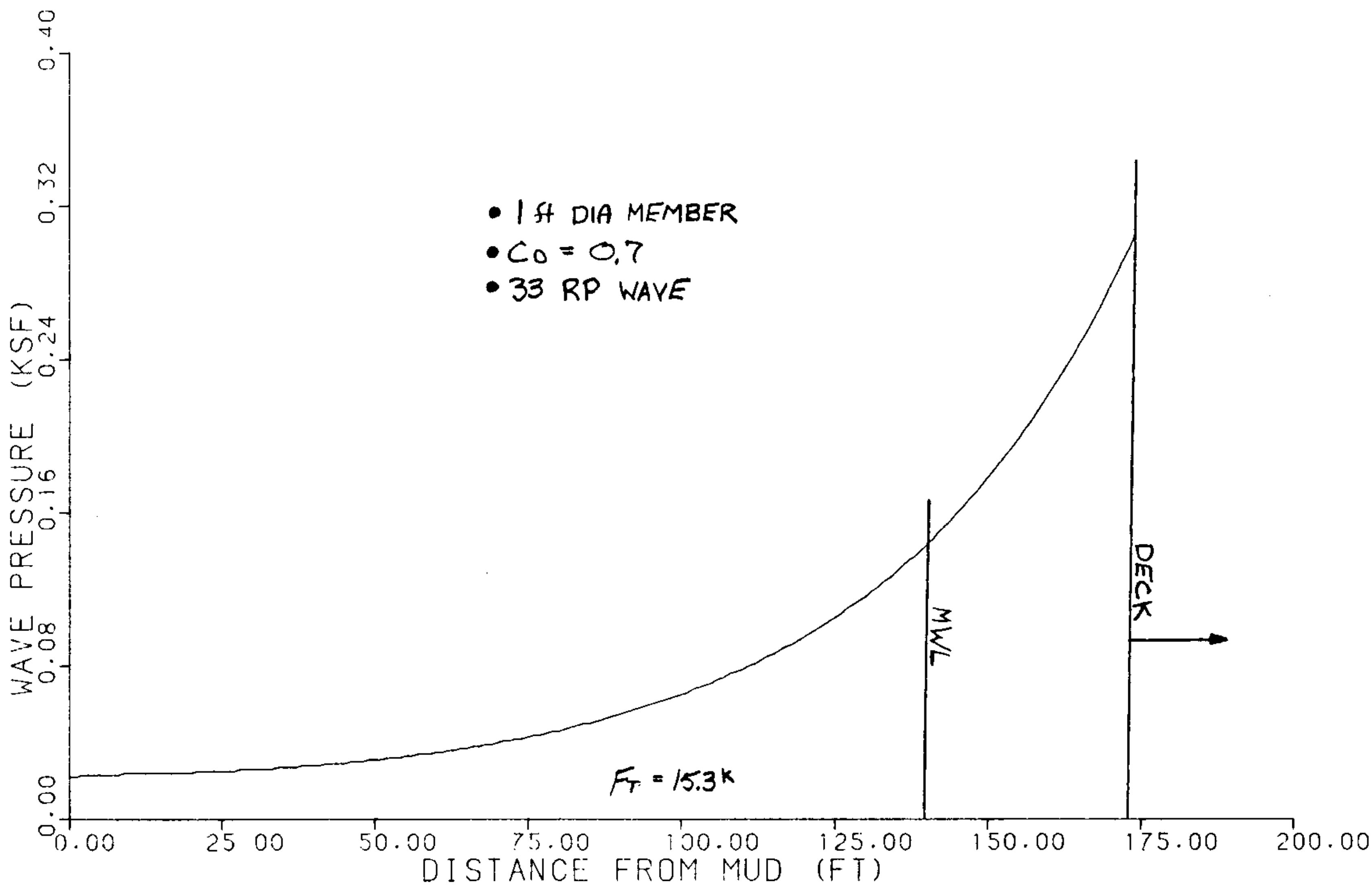
CURRENT SPEED VS. RETURN PERIOD - PLATFORM "A"



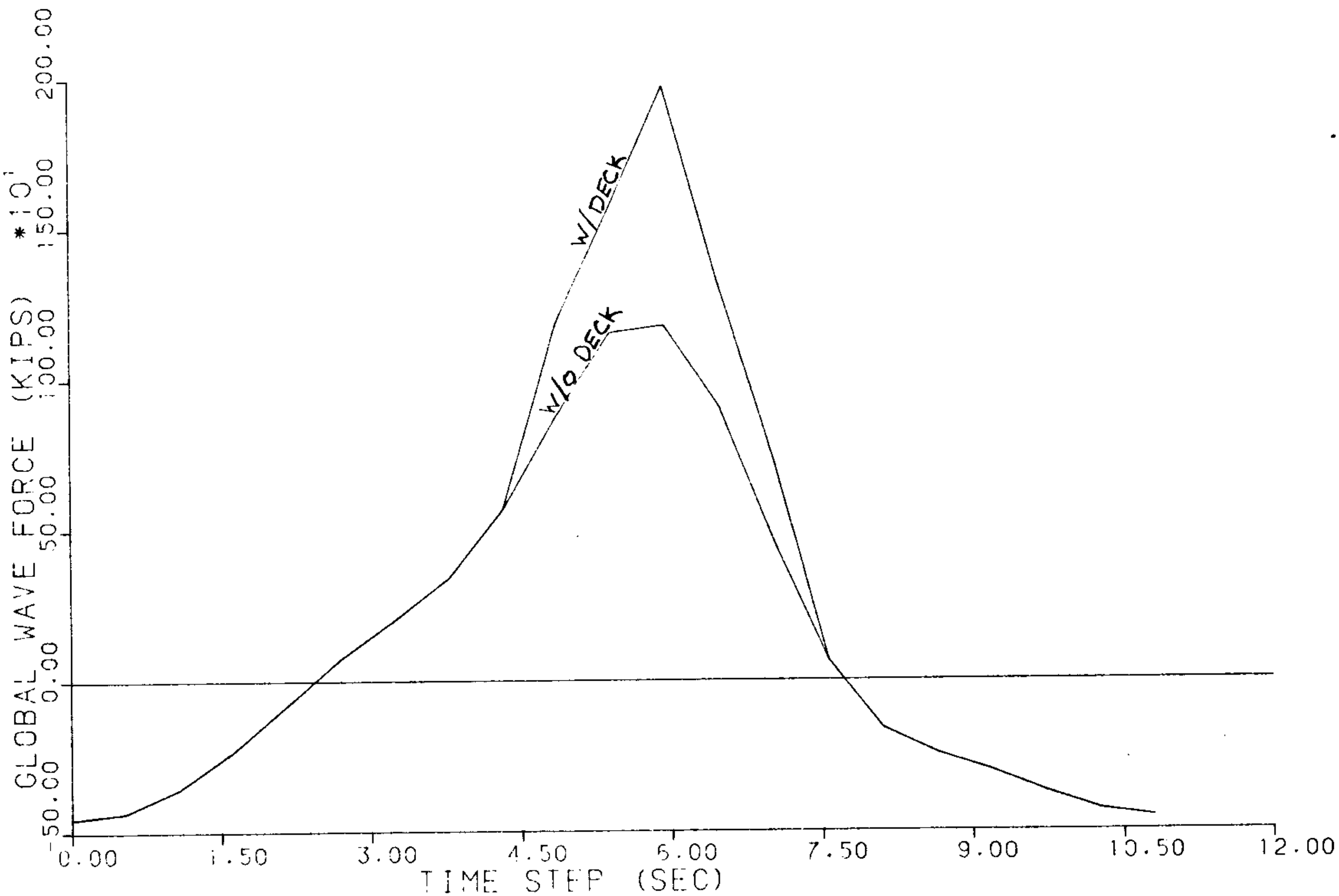
WAVE SURFACE PROFILE PLATFORM A



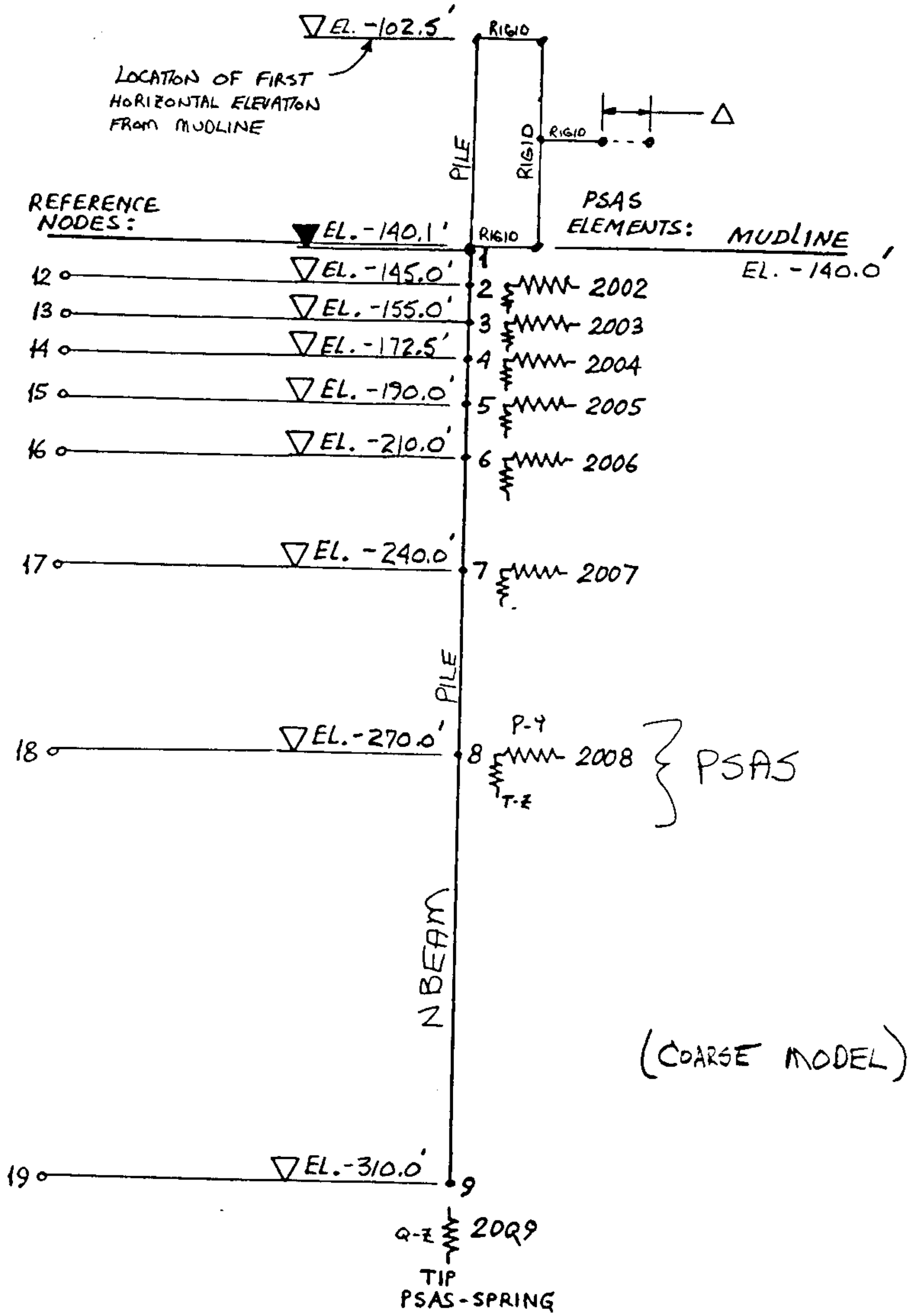
WAVE KINEMATICS - PLATFORM A



WAVE PRESSURE PROFILE - PLATFORM A



WAVE FORCES ON PLATFORM A - 100 YR WAVE



TYPICAL SINGLE PILE MODEL
(PLATFORM A)

PLATFORM "A"

FOUNDATION CHARACTERIZATION

Soils

Depth	Soil
0′ to 10′	Soft Clay (Recent)
10′ to 141′	Stiff Clay (Pleistocene)
141′ to 172′	Silty Sand (Pleistocene)
172′ to 182′	Stiff Clay (Pleistocene)

Soils Strength

Depth	S_u	ϵ_{50}	γ_i
0′ to 10′	400 psf	0.5%	50 pcf
10′ to 25′	1600 psf	0.5%	55 pcf
25′ to 142′	1400 psf	0.5%	55 pcf
142′ to 172′	ϕ = 25 deg.	0.5%	60 pcf

Piles (Welded)

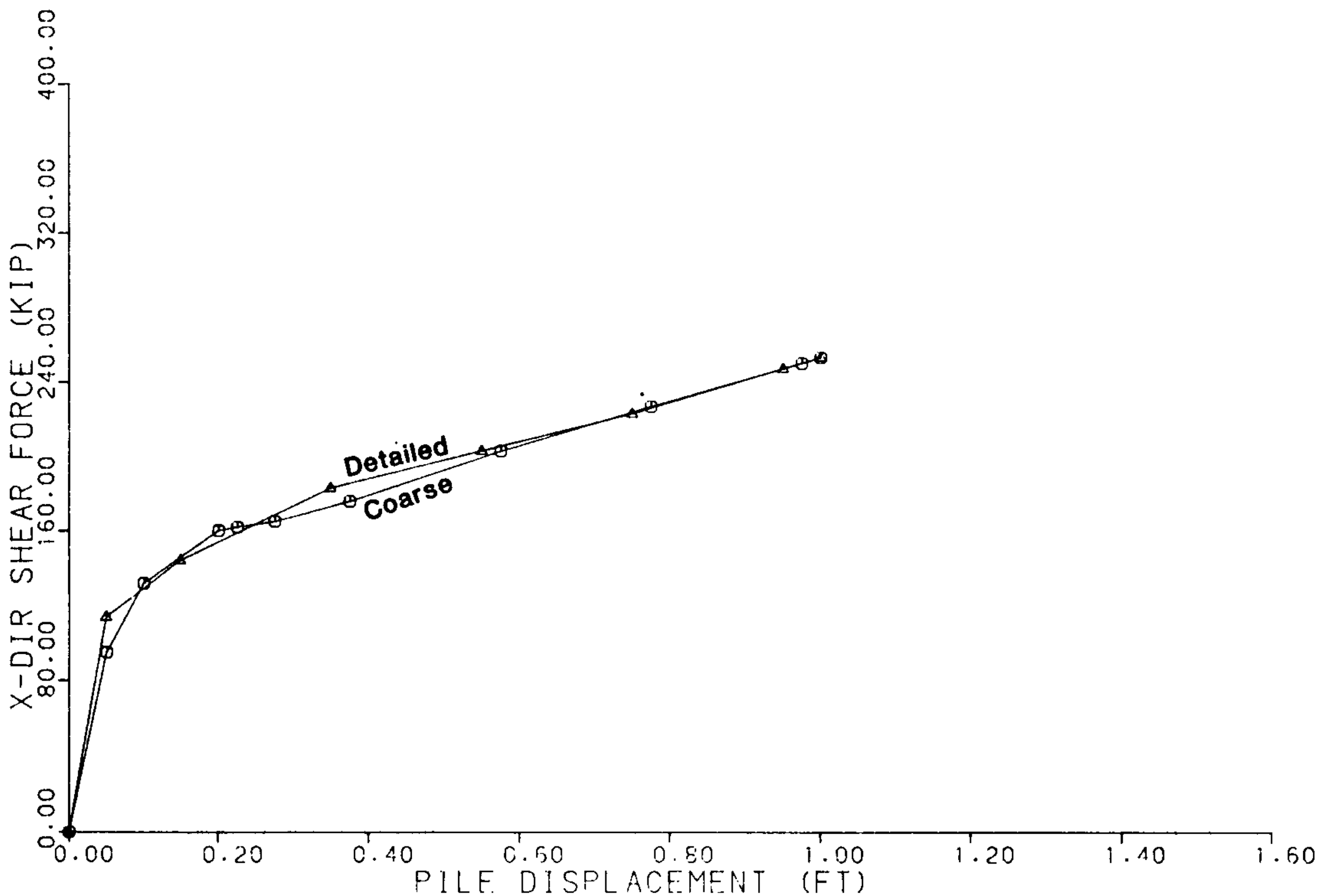
4 Total
170′ Penetration
36" ϕ with 1" Wall Thickness
σ_y = 45 ksi

Conductors

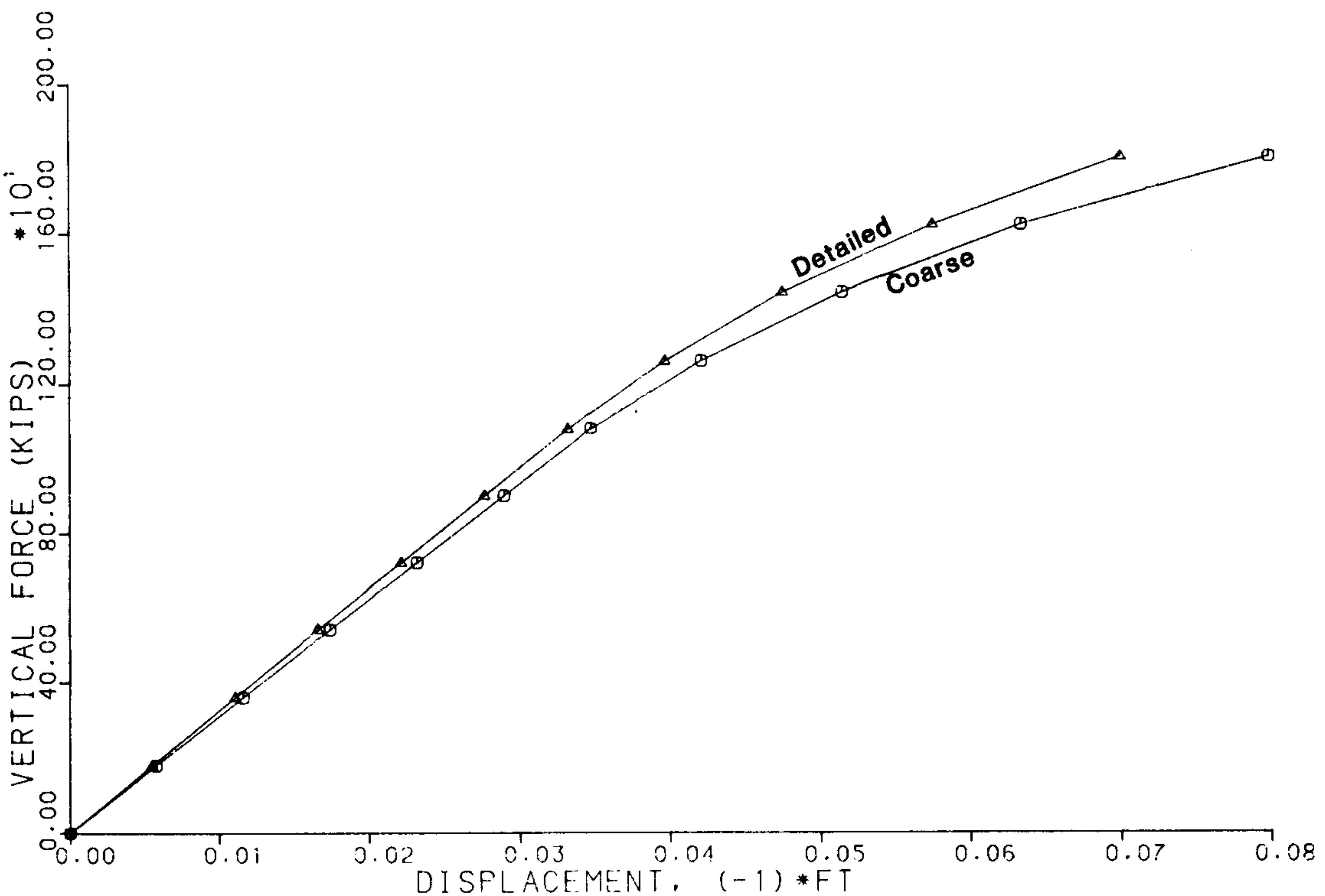
9 total

8 20" ϕ with 5/8" Wall Thickness
σ_y = 45 ksi

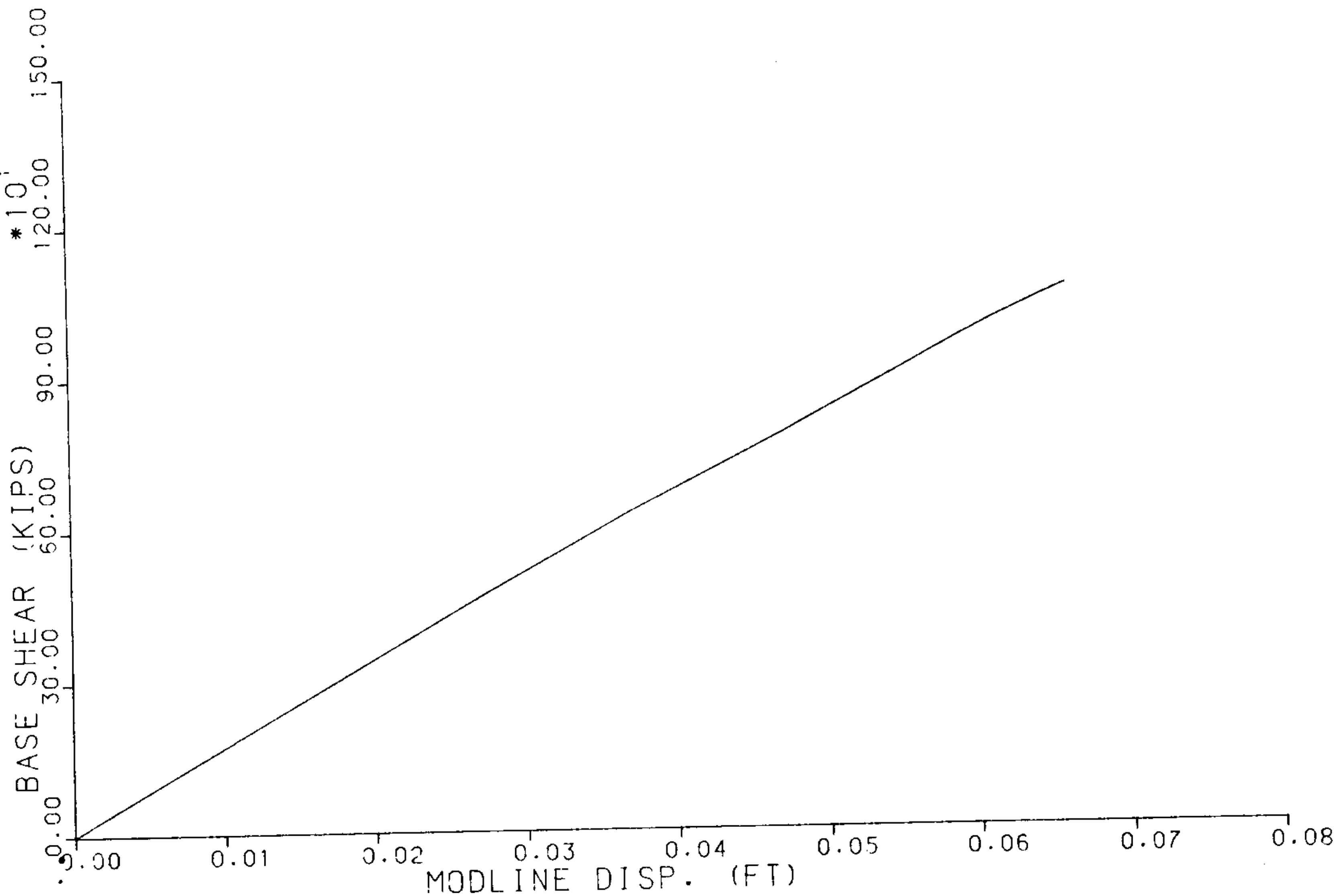
1 Center Conductor Pile
30" ϕ with 5/8" Wall Thickness
σ_y = 45 ksi



PLATFORM "A". SINGLE PILE RESPONSE TO X-DIR LOAD



PLATFORM "A". SINGLE PILE RESPONSE TO Z-DIR.LOAD



PLATFORM "A" LOAD-DISPLACEMENT CURVE. X - WAVE.

APPENDIX B

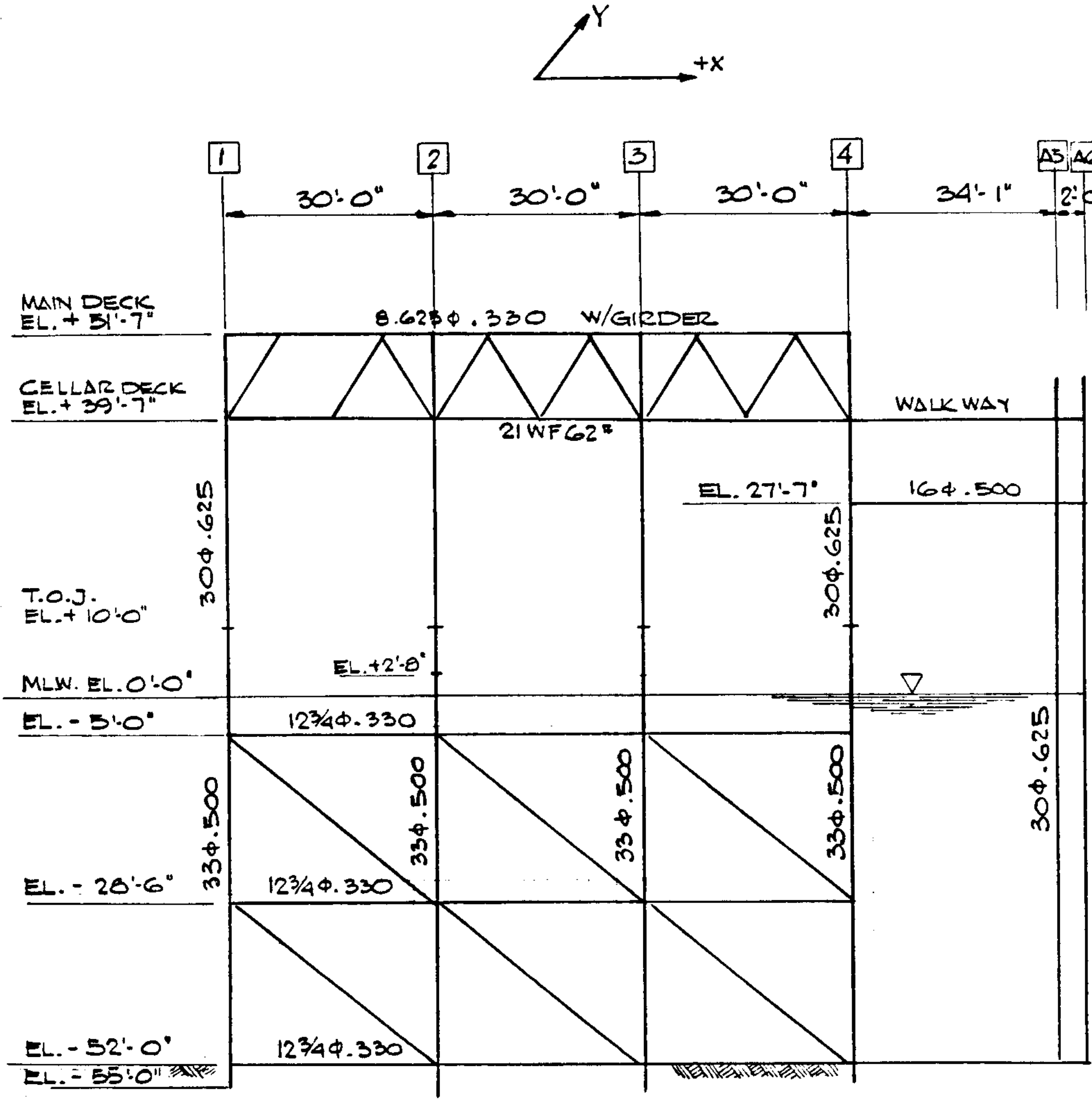
PLATFORM "B" EVALUATION

APPENDIX B

PLATFORM "B" EVALUATION

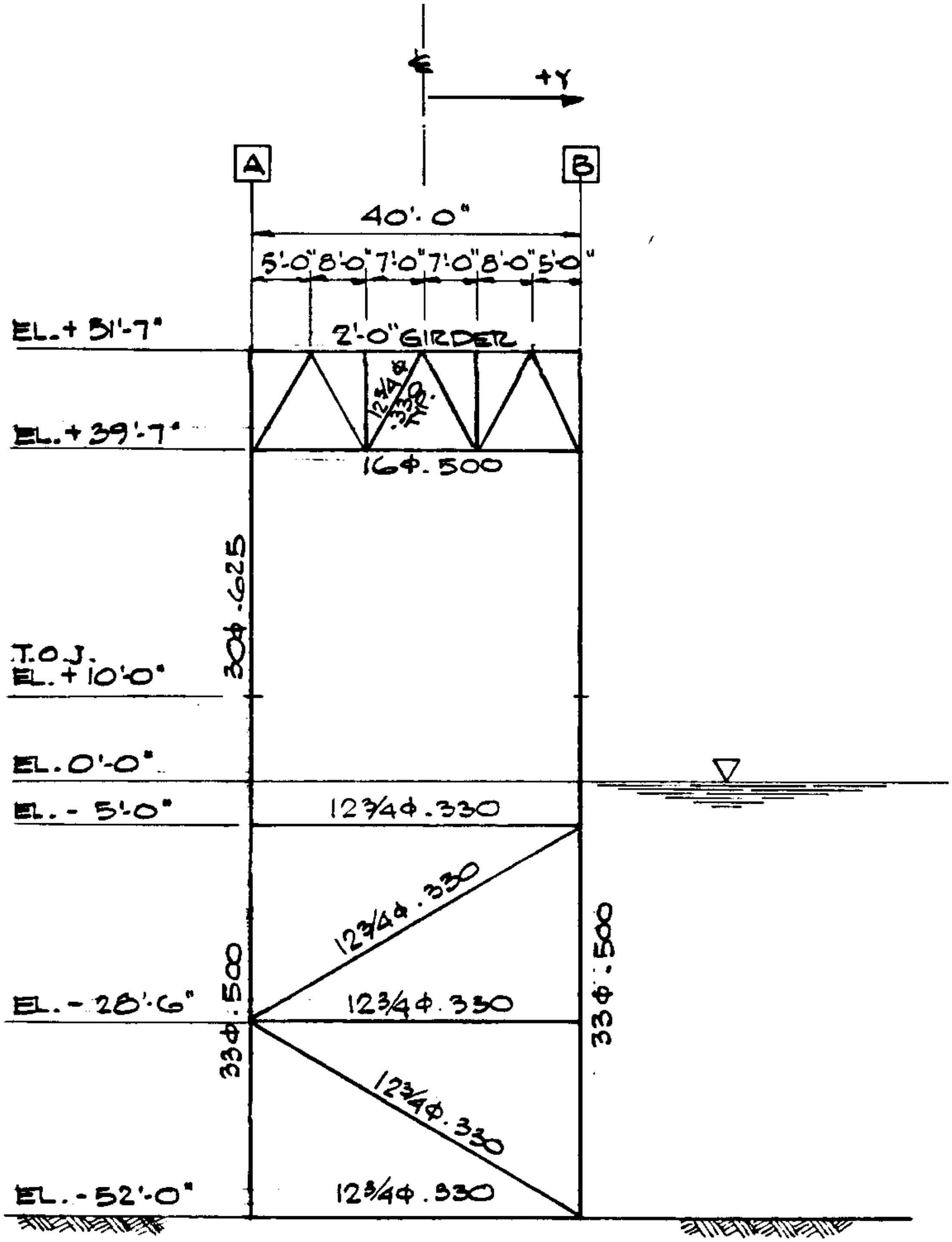
Page	Description
B.1 - B.3	Typical member sizes. Note 8-5/8 in. pipes supporting conductors at each horizontal.
B.4 - B.7	Detailed platform background information.
B.8	Damage Report Summary.
B.9 - B.10	Location of damaged members.
B.11 - B.14	General views of three-dimensional computer model. Note same orientation of all vertical diagonals Row A (page B.12). Orientation is same for Row B.
B.15 - B.17	Storm surge, wind speed and current speed return period information. These conditions are assumed to coexist with the wave of same return period. The plateaus indicate maximums due to shallow water depth at site.
B.18	Wave horizontal water particle velocities for selected return hurricane return periods. Note high velocities at crest (40 fps) due to near breaking wave. Also note that the 100-year wave has lower velocity at deck elevation than smaller 28-year wave. Since the deck equipment is "lumped" at this elevation in the computer model, this lower velocity for larger waves results in a slight decay in total lateral force with increasing wave height as shown by the dotted line in Figure 4-10.
B.19	Wave pressure distribution for hurricane wave just under deck and Norther wave crest caused by high horizontal water particle velocities.
B.20	Comparison of Platform A and Platform B hurricane wave pressure profiles. This figure indicates the magnitude of the Platform B theoretical wave crest pressures. The "actual" curve indicates the pressures that might actually exist (based upon test data).

B.21	Wave force time history with and without deck. Note the "jump" of almost 1000 kips for the wave in the deck. See Section 4.3 for further discussion.
B.22	PSAS single pile model. PSAS models were developed for all piles and conductors included in the 3-D platform model.
B.23	Soil and pile data used for PSAS analysis.
B.24 - B.25	Comparison of detailed and coarse single pile models for lateral and axial directions. The detailed model had 20 elements. The coarse model had 8 elements. The coarse model (with fewer elements) was the one eventually installed in the 3-D platform model. The comparison is required to ensure the coarse model adequately models the soil-pile interaction.
B.26	Pile top (mudline) horizontal displacement during Y-direction (controlling condition) ultimate capacity analysis.
B.27	This figure shows load-displacement curves for the "original" Platform B model and the "revised" Platform B model. The "original" model was found to have deck legs with insufficient stiffness and moment capacity. This problem was corrected ("revised" model) and the analysis rerun in the critical "Y" direction. The "original" analysis proceeds with a large displacement for a given load (i.e. "soft" structure) until the deck legs yield at approximately 760 kips of base shear. The "revised" analysis follows a stiffer structural response until some of the braces "buckle" at which time the structure reaches it maximum capacity of 860 kips. The dotted line indicates the results of the analysis using nonlinear truss elements for the braces which do not shed load at buckling. The solid line shows the projected actual platform response if load shedding strut elements were used. Since the differences between the two sets of ultimate capacity were minimal, it was decided to continue the AIM evaluation using the results developed from the "original" Platform B analysis.



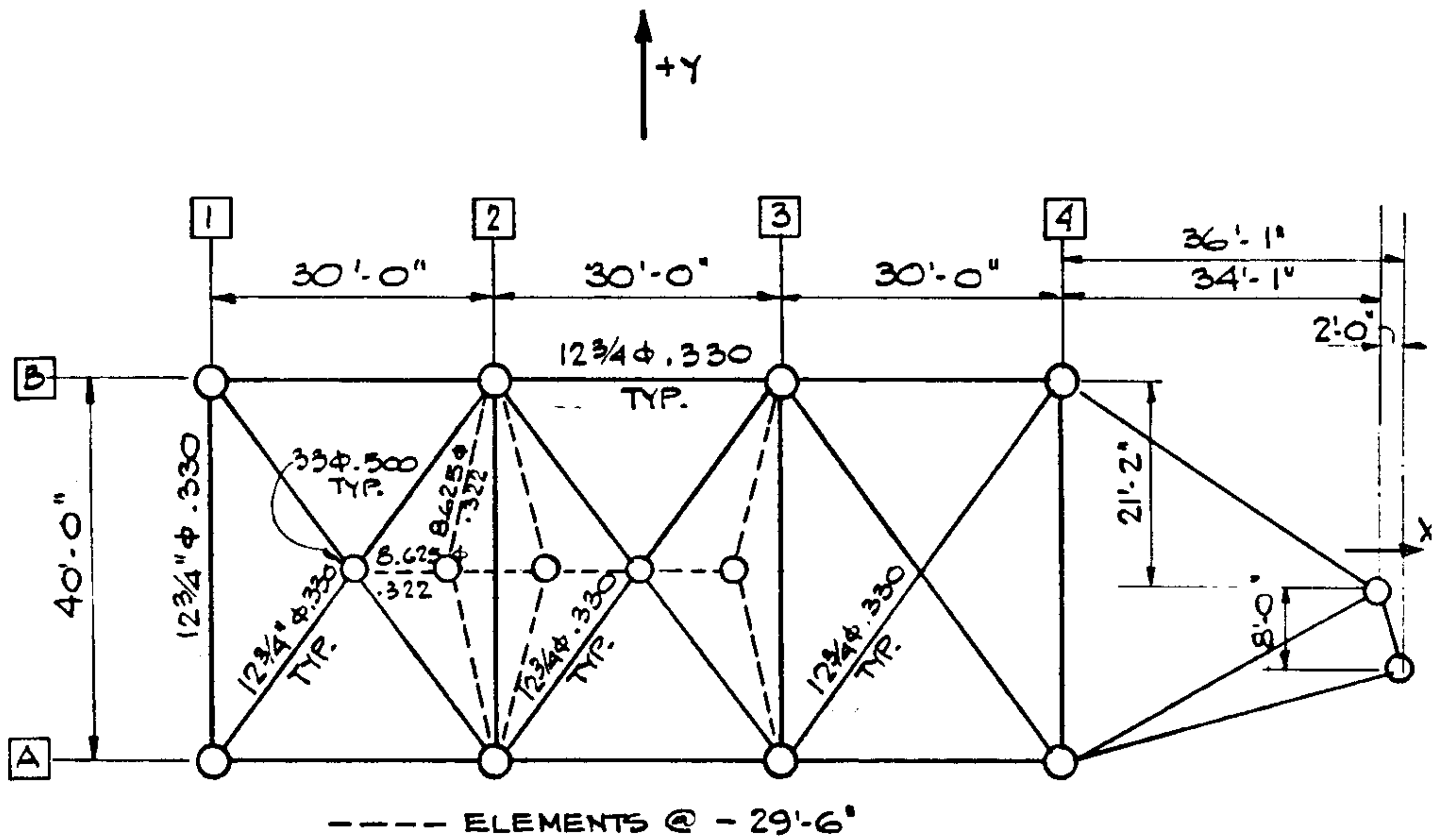
ELEV. @ ROW A

PLATFORM B



ELEV. @ ROW 1

PLATFORM B



PLAN @ ELEV. (-)28'-6"

I. VITAL STATISTICS

A. Property Information

Location: Central Gulf of Mexico

Water Depth: 52 Feet MLW

Installed: 1959

Number of Legs: 8

Number of Jacket Elevations: 3

Top of Jacket Dimensions: 40 by 90 Feet

Leg Batter: Vertical

Number of Wells: 5 Design and 7 Presently

Location of Wells:

5 in Center of Jacket (30" ø) and

2 Braced Outboard (20" ø)

Type of Platform: Tender Drilling and Production Platform

Number of Boat Landings: 1

Number of Barge Bumpers: 2

Piles Grouted: Yes

Pile Diameter: 30 Inches

Pile Penetration: 150 Feet

Number of Risers: 2

Type of Cathodic Protection System: Sacrificial Anodes

Elevation of Top of Jacket: -4 Feet

Number of Deck Levels: 2

Elevation of Cellar Deck: +40 Feet

Elevation of Top Deck: +58 Feet

Elevation of Sump Deck: N/A

Plan Dimension of Decks: 40 by 90 Feet

Deck Covering: Grating

B. <u>Personnel Information</u>

Quarters: No - Manned Only During Daylight Hours

Helideck: Yes

C. <u>Production Information</u>

Production Equipment: Gas Train through dehydration

Production: Natural Gas

D. <u>Environmental Impact Information</u>

Pertinent Data: None

E. <u>Risk Potential Information</u>

Expected Future Life: 5 Years

II. LIFE HISTORY

A. Design Information

Soil Boring: Yes

Environmental Report: Yes

Design Specification: No

Design Report: No

Construction Drawings: Yes

B. Construction Information

Fabrication Date: 1963

Fabrication Specification: No

Primary Materials Used: Mild Steel (A36)

Joint Material: Mild Steel (A36)

Fabrication Inspection Records: No

Splashzone Material: Wrap and Paint

Paint System: Two Coat

Installation: Derrick Barge

Piles to Grade? Apparently

Driving Records: No

C. Operational Information

Drilling Phase: 1959-1960

Structural Modifications During Drilling: None Known

Incidents During Drilling: None Known

Production Phase: 1960 to Present

Well Workover: Yes, with Drilling Tender and Jackup

Known Incidents During This Phase: No

D. Accident Information

Boat Possibly Inside Jacket

E. Maintenance and Present Status

Summary of Inspections: 1985

Discoveries Above Water: Yes Both Times

Discoveries Below Water: Yes Both Times

List of Structural Defects:

- Severed Horizontal Member at -4
- Cracked Horizontal Member at -4

Status of Cathodic Protection System: Initial System Depleted, Retrofitted System Still Functioning

Status of Above Water Paint System: Areas of Corrosion

Present Marine Growth: 2.0 Inches from Waterline to -52

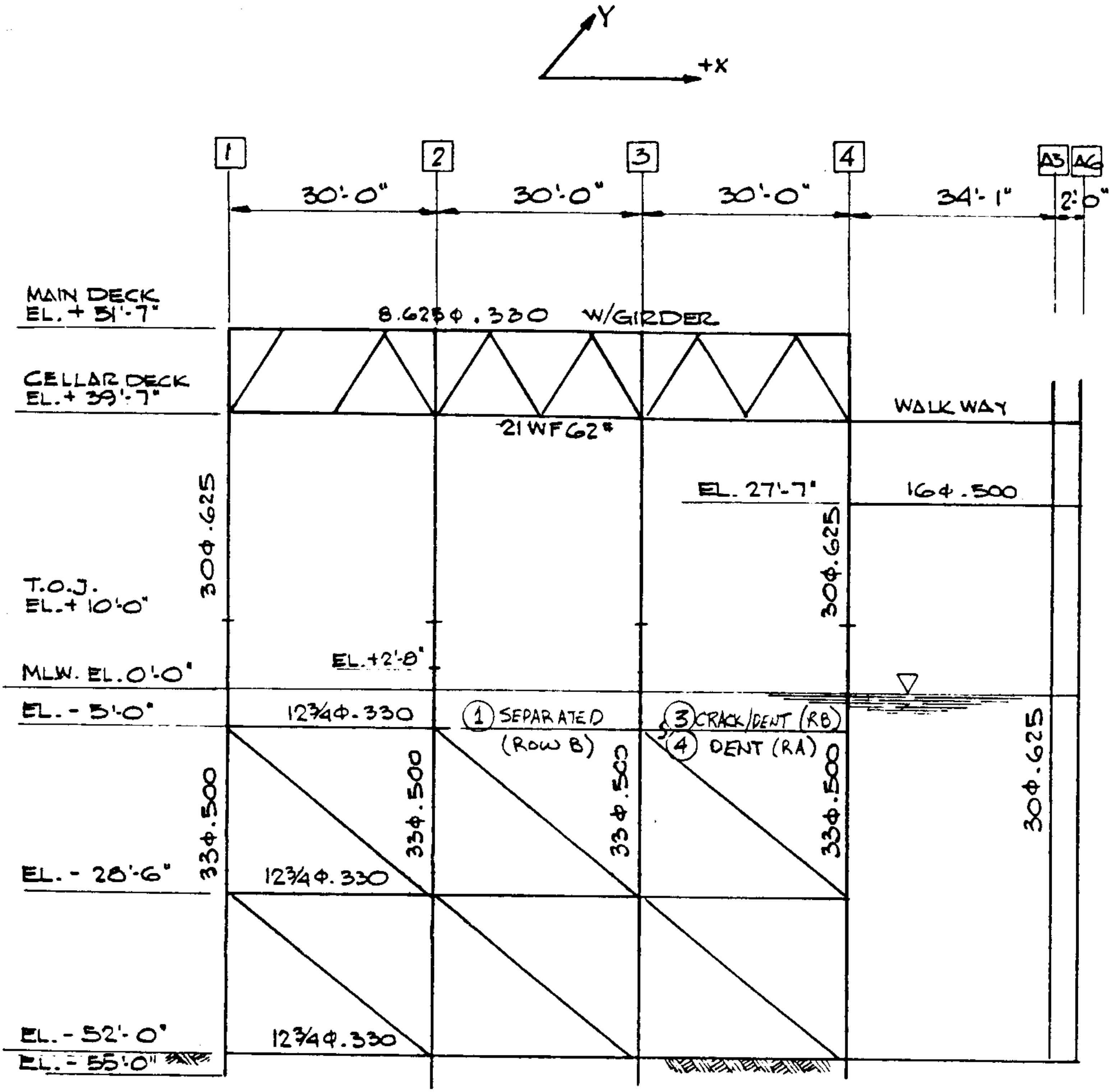
Scour at Base: Three Feet of Scour

History of Structural Repairs: None

PLATFORM "B"

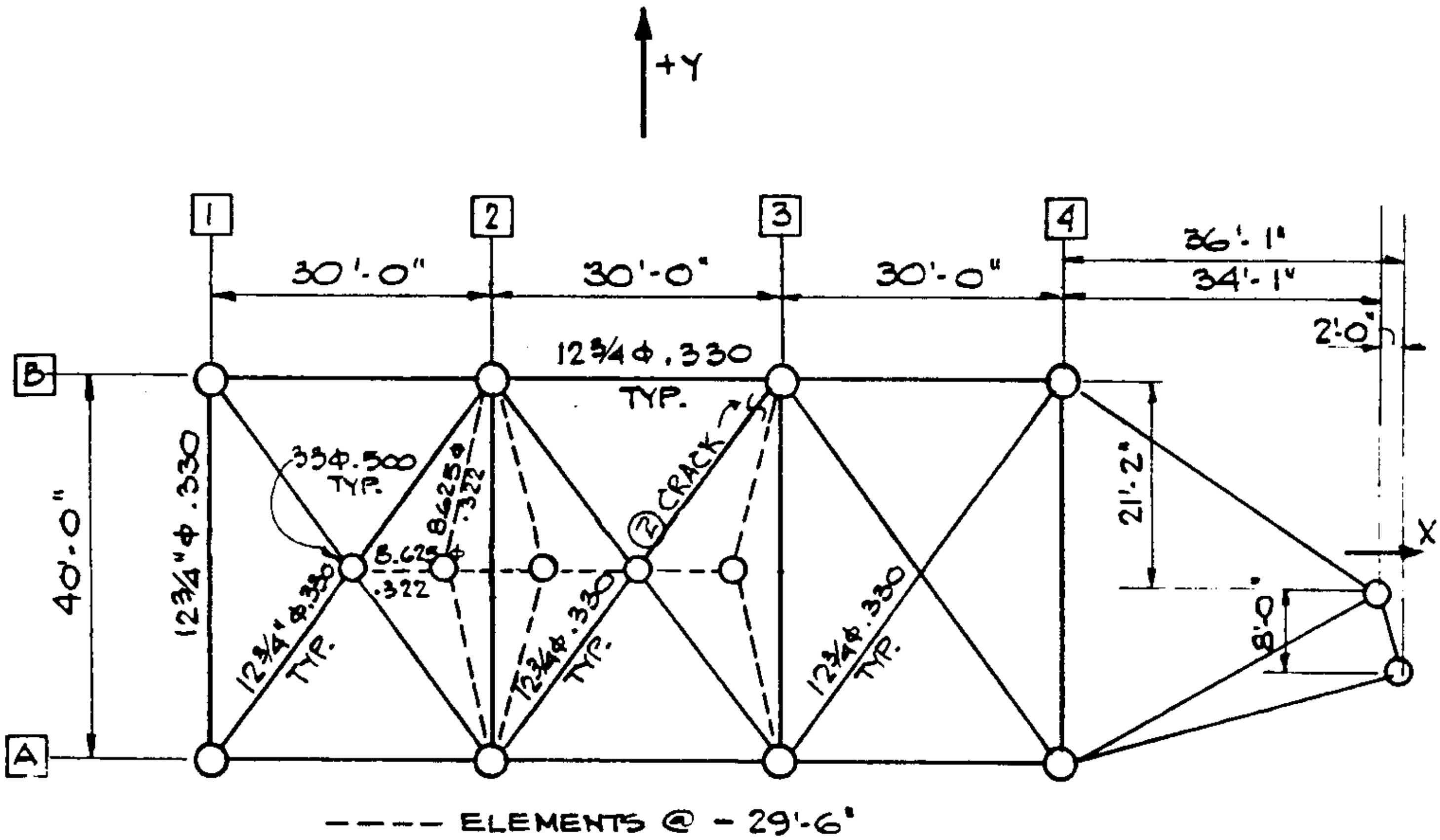
DAMAGE REPORT SUMMARY

ITEM NO.	LOCATION	DAMAGE
1	Horizontal Face Member Row B B2 to B3 at -4′	Complete Separated from Leg at B2 Numerous Dents
2	Horizontal Interior Diagonal -4′ B3 to A2	Cracked at B3 from 11:30 to 4:30 Crack Length = 20"
3	Horizontal Face Member Row B B4 to B3 at -4′	Dent 56" x 11" x 2" Deep 4" Crack on Bottom of Dent
4	Horizontal Face Member Row A A3 to A4 at -4′	Dent 10" x 8" x 1/2" Deep

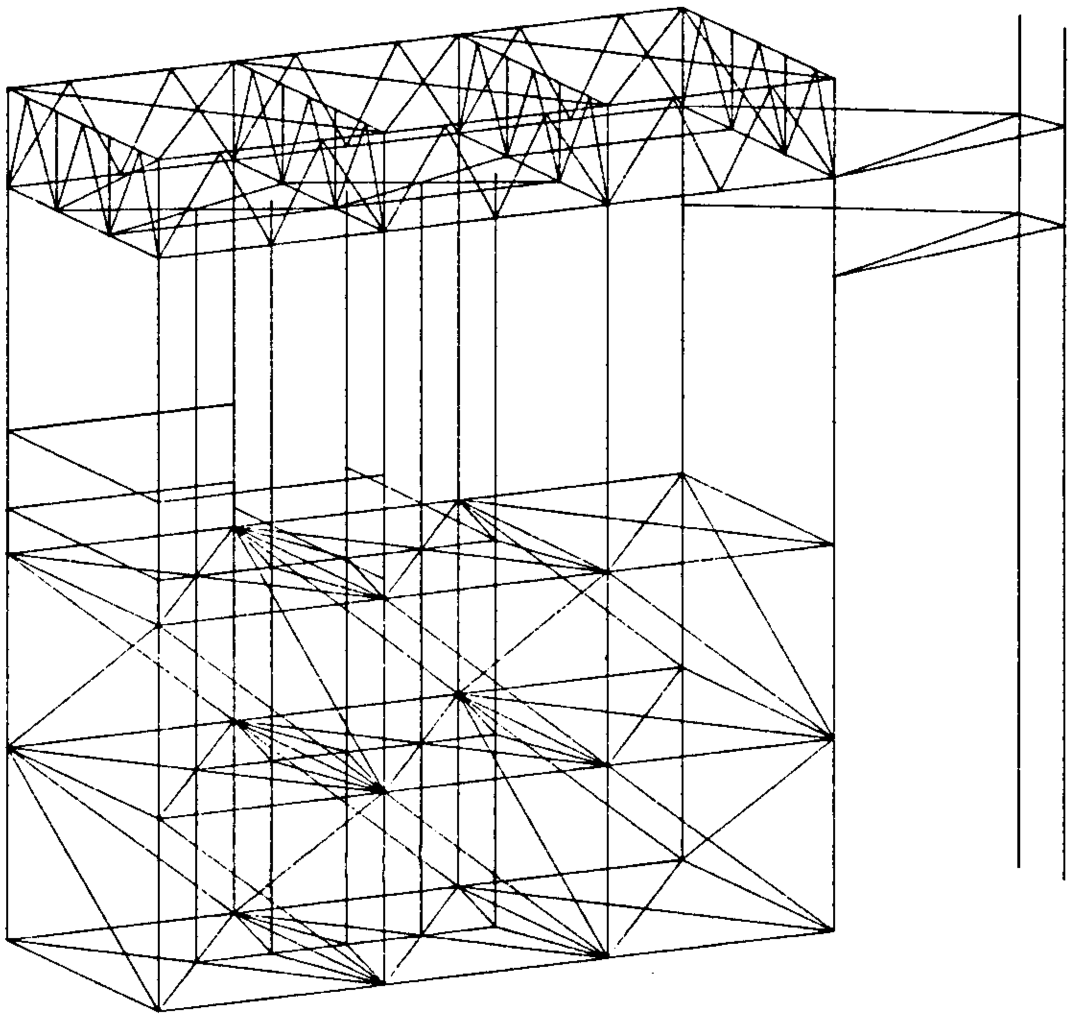


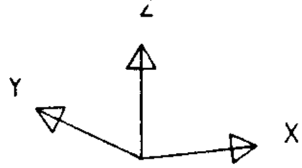
ELEV. @ ROW A

PLATFORM B



PLAN @ ELEV. (-)28'-6"





AIM 2, B PLATFORM

PLATFORM ISOMETRIC VIEW

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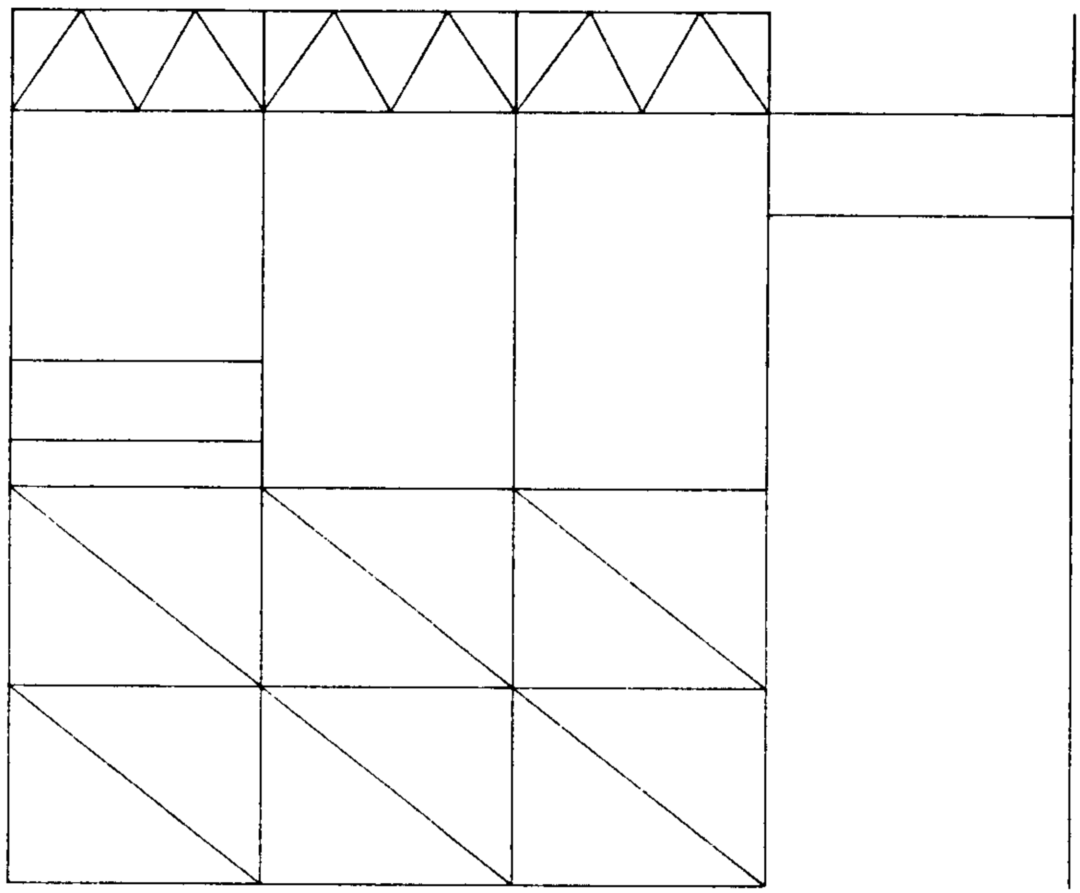

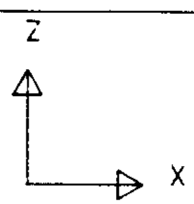

GLOBAL AXES

AIM 2, B PLATFORM

ROW A

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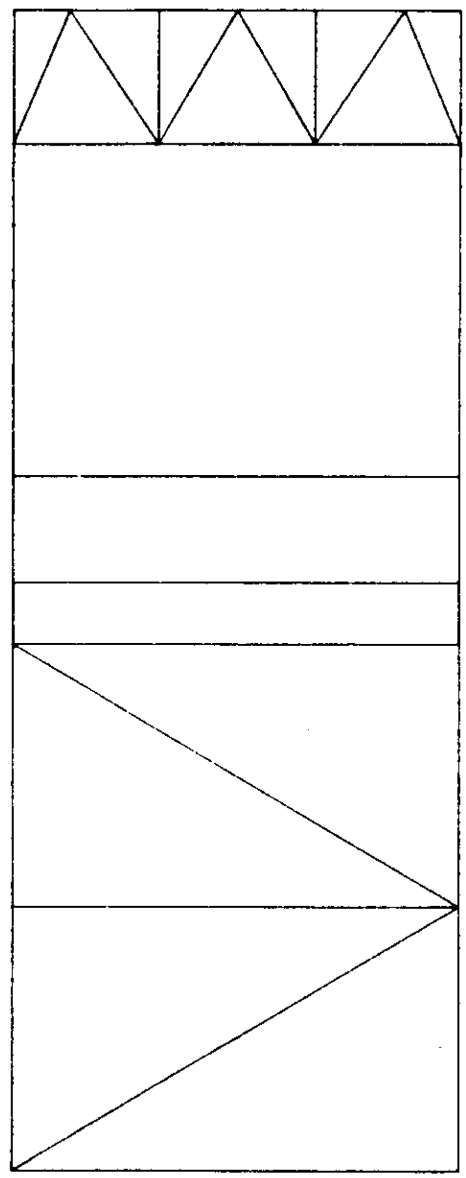

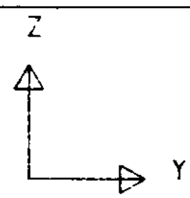

GLOBAL AXES

AIM 2, B PLATFORM

ROW 1

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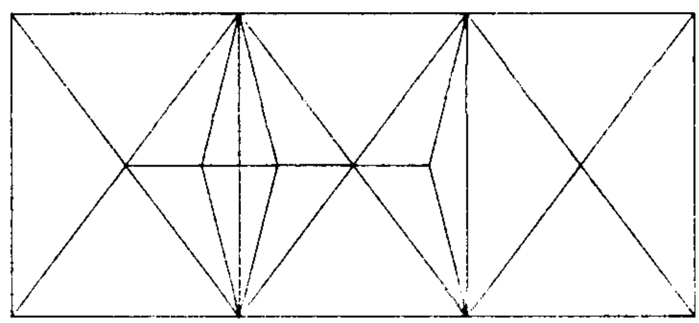

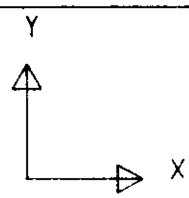

GLOBAL AXES

AIM - 2 PROJECT. PLATFORM "B"

PLAN AT ELEVATION -5 FT

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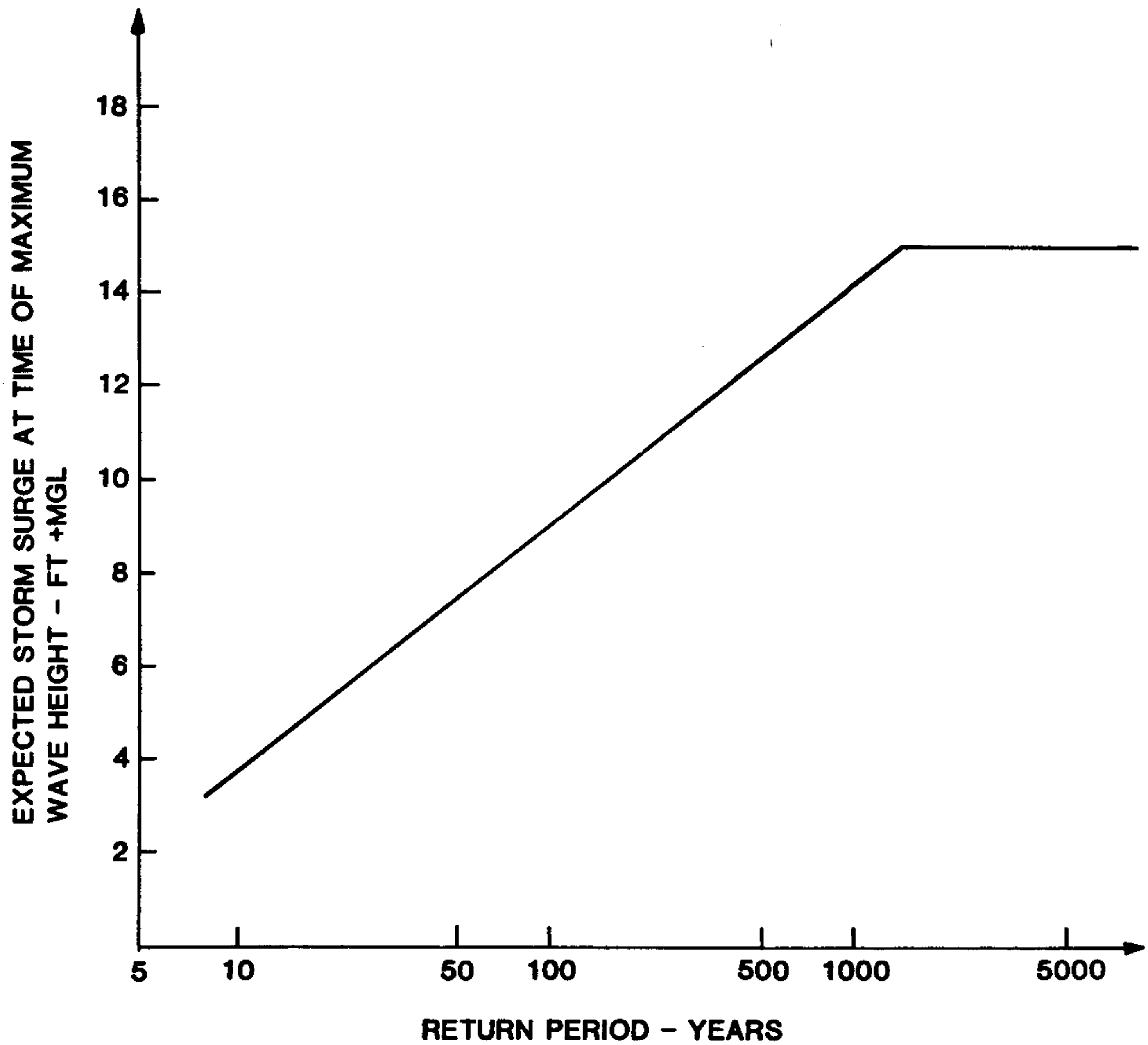
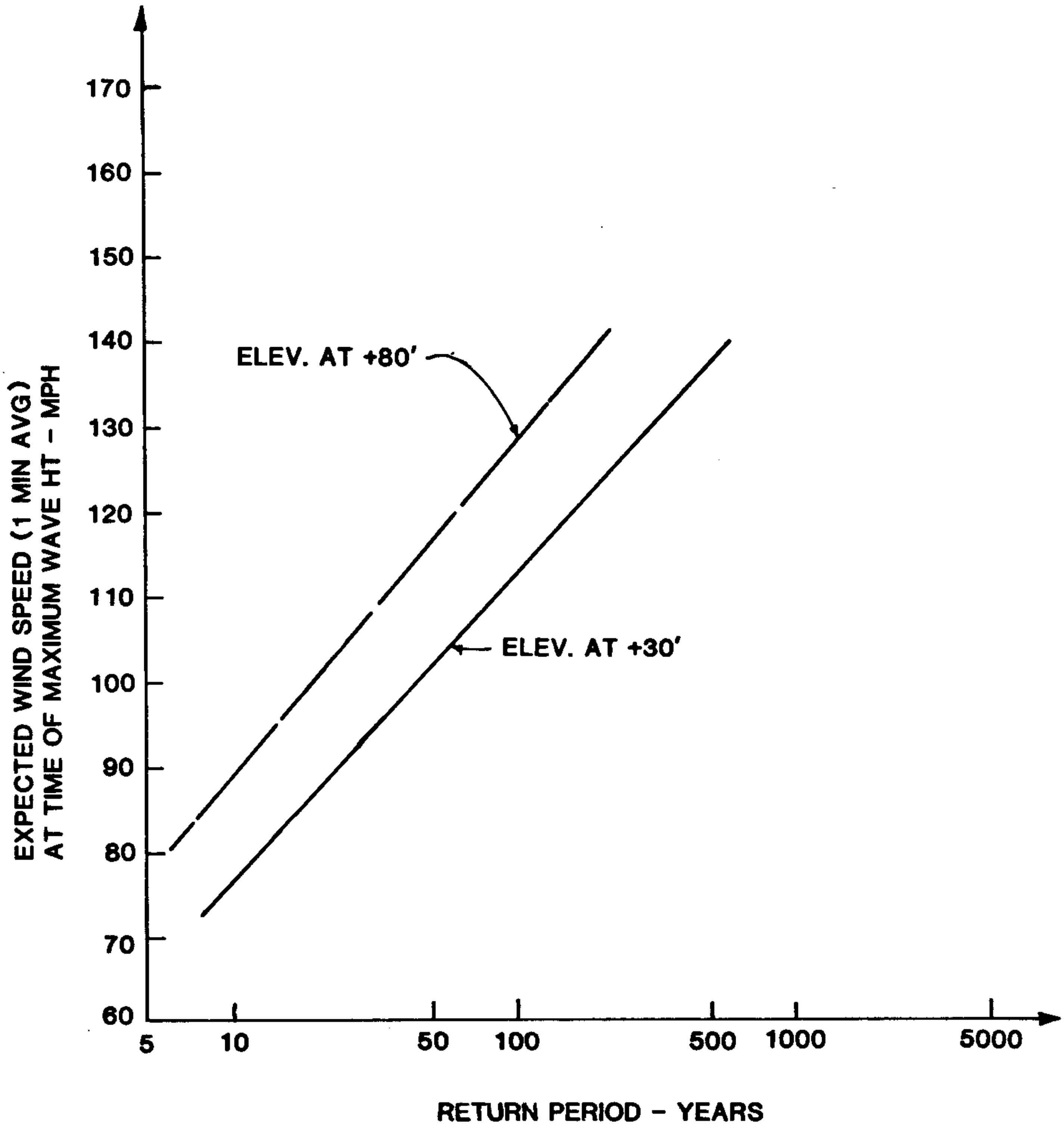
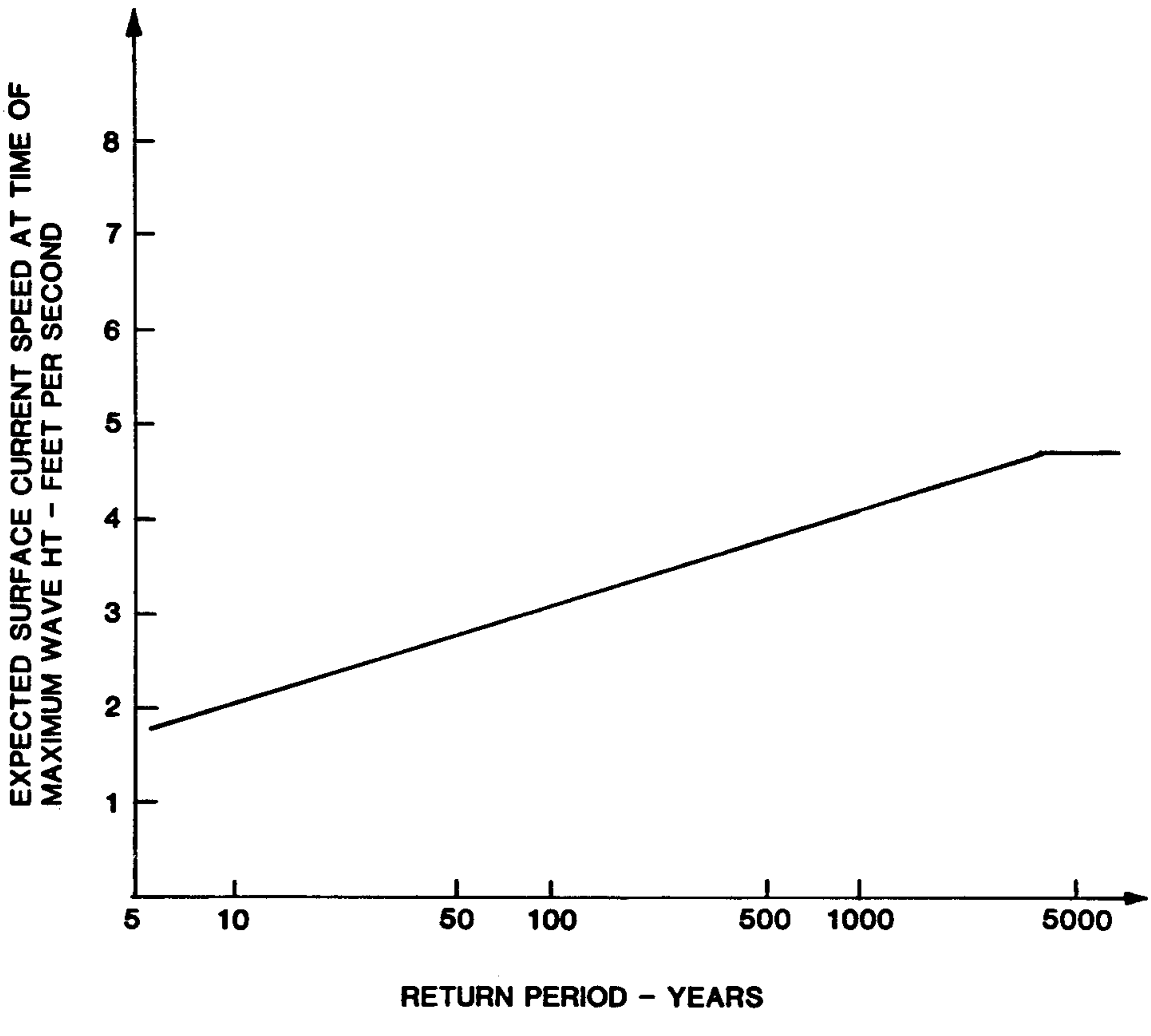


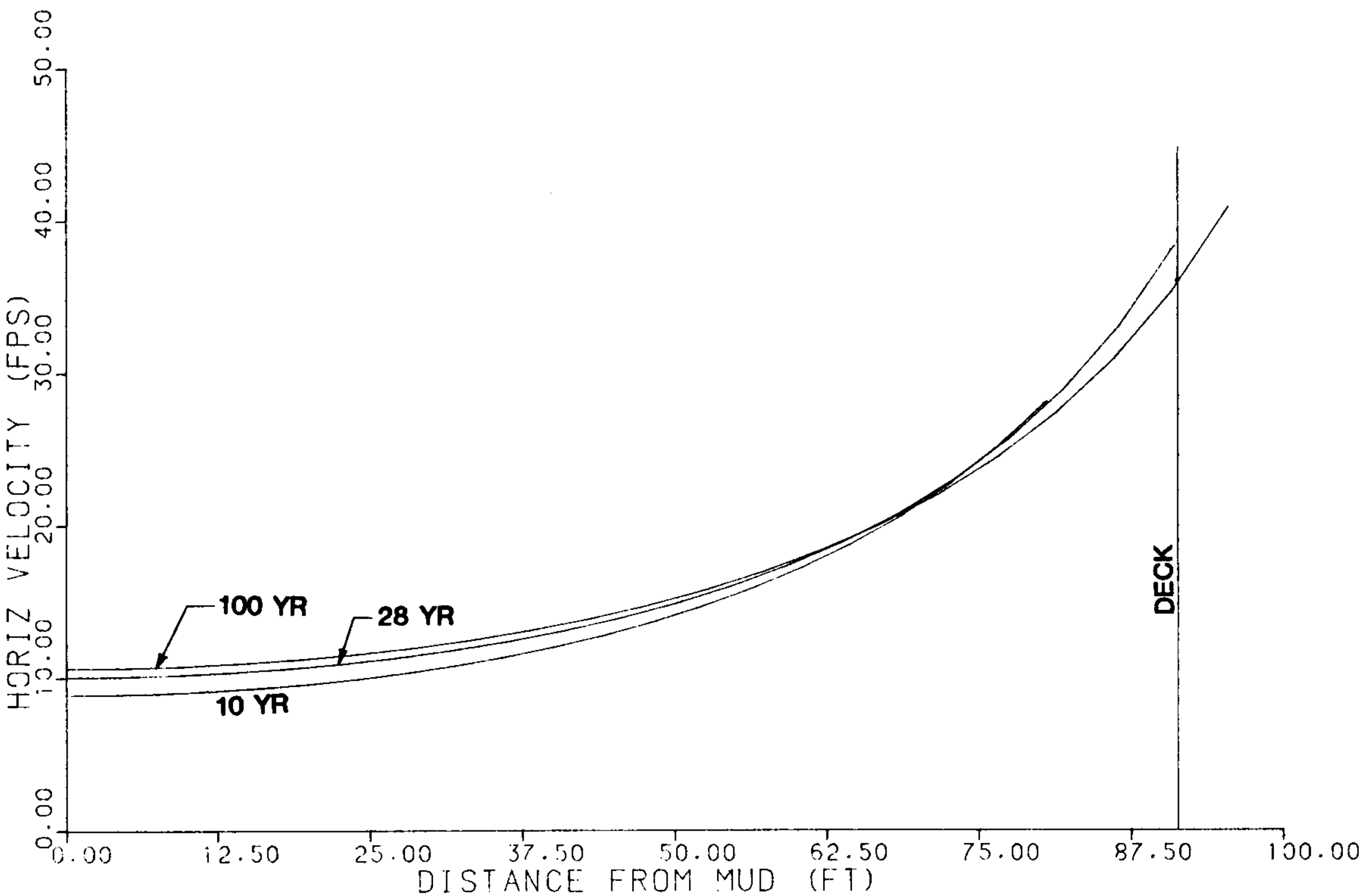
STORM SURGE VS. RETURN PERIOD - PLATFORM "B"



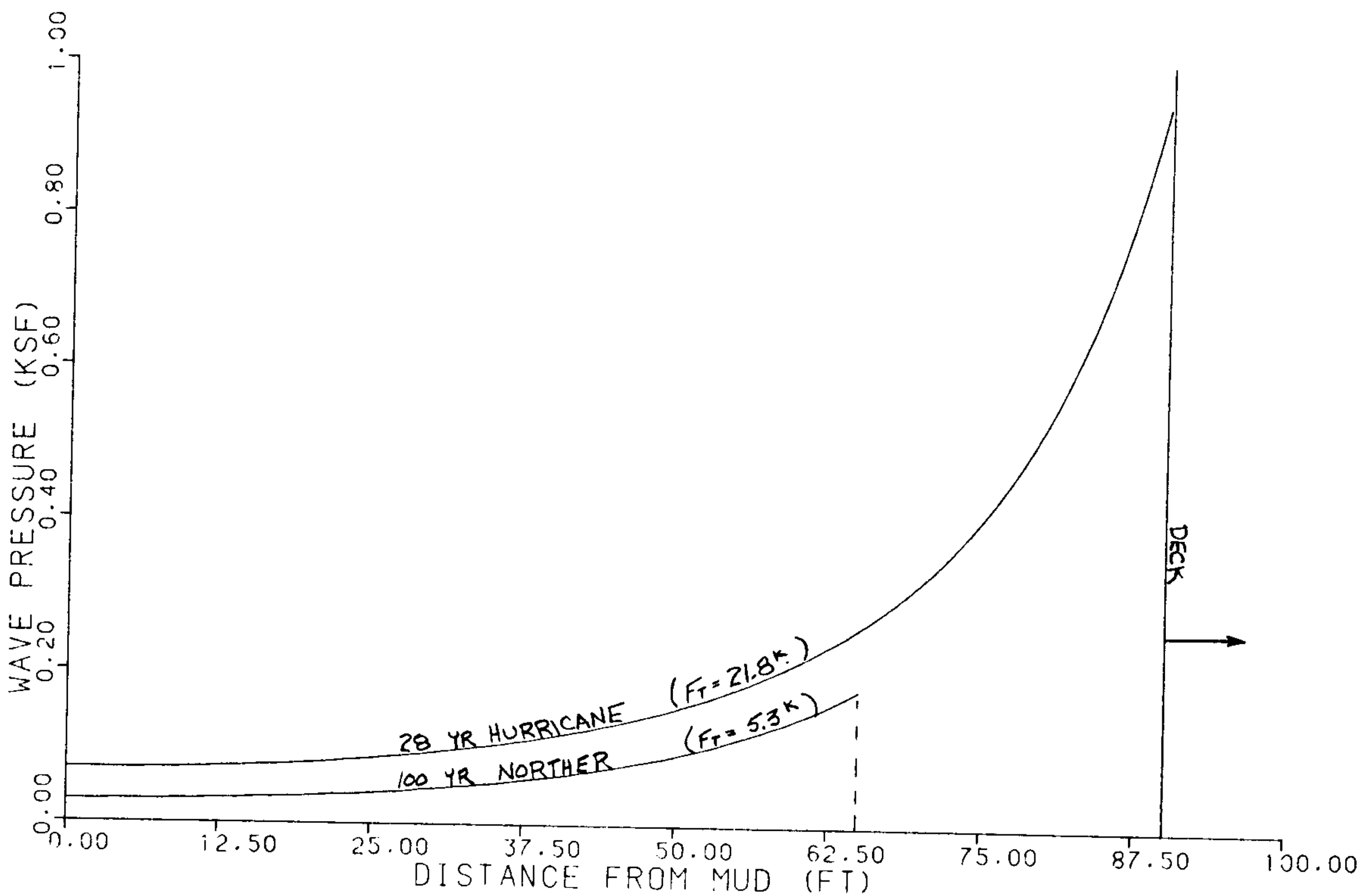
WIND SPEED VS. RETURN PERIOD - PLATFORM "B"



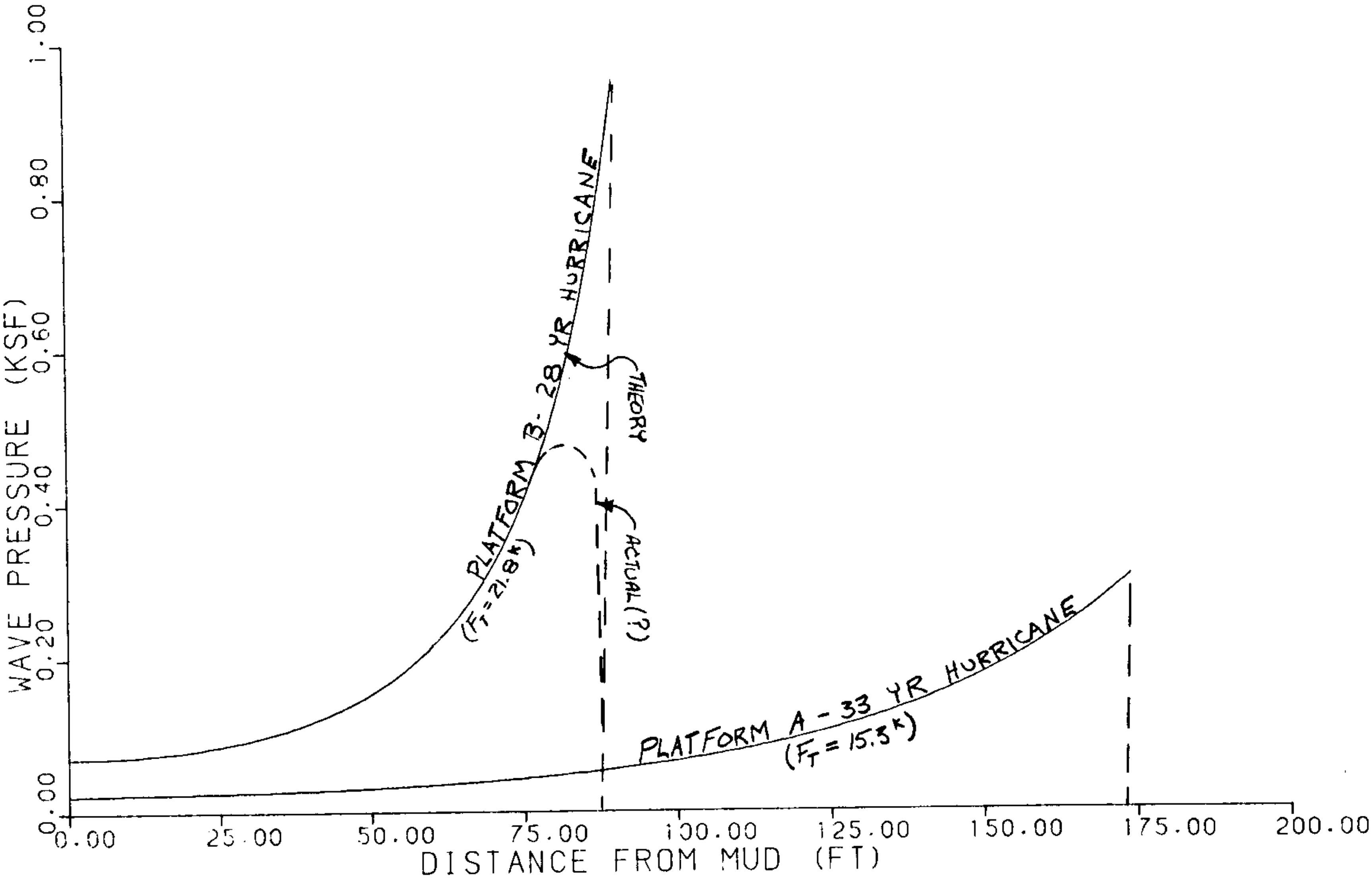
CURRENT SPEED VS. RETURN PERIOD - PLATFORM "B"



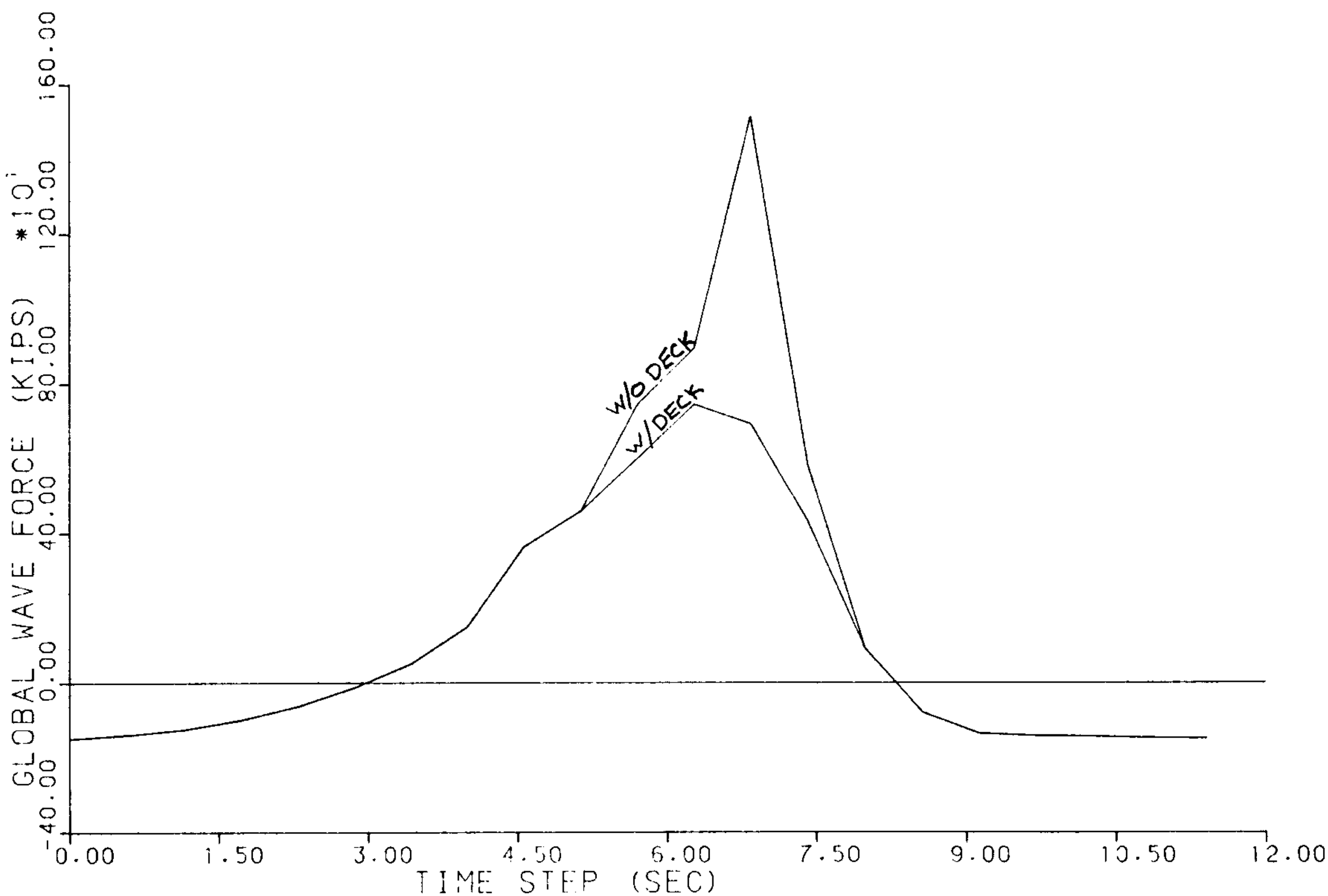
WAVE KINEMATICS - PLATFORM "B"



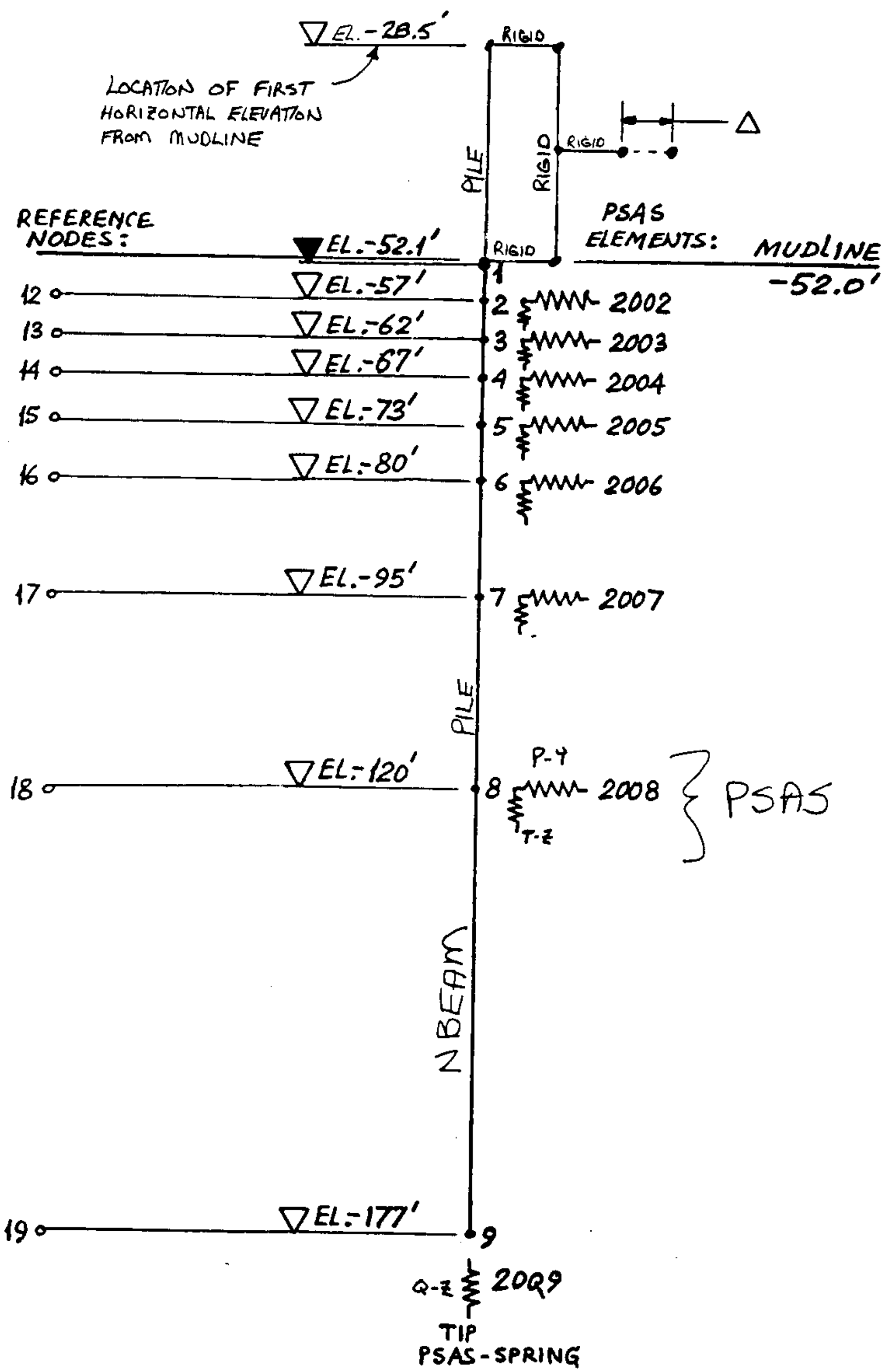
WAVE PRESSURE PROFILE - PLATFORM B



WAVE PRESSURE PROFILE - PLATFORMS A & B



WAVE FORCES ON PLATFORM B - 100 YR WAVE



TYPICAL SINGLE PILE MODEL (PLATFORM B)

PLATFORM "B"

FOUNDATION CHARACTERIZATION

Soils

Depth	Soil
0′ to 6′	Soft Clay (Recent)
6′ to 120′	Stiff Clay (Pleistocene)
120′ to 170′	Dense Sand (Pleistocene)

Soils Strength

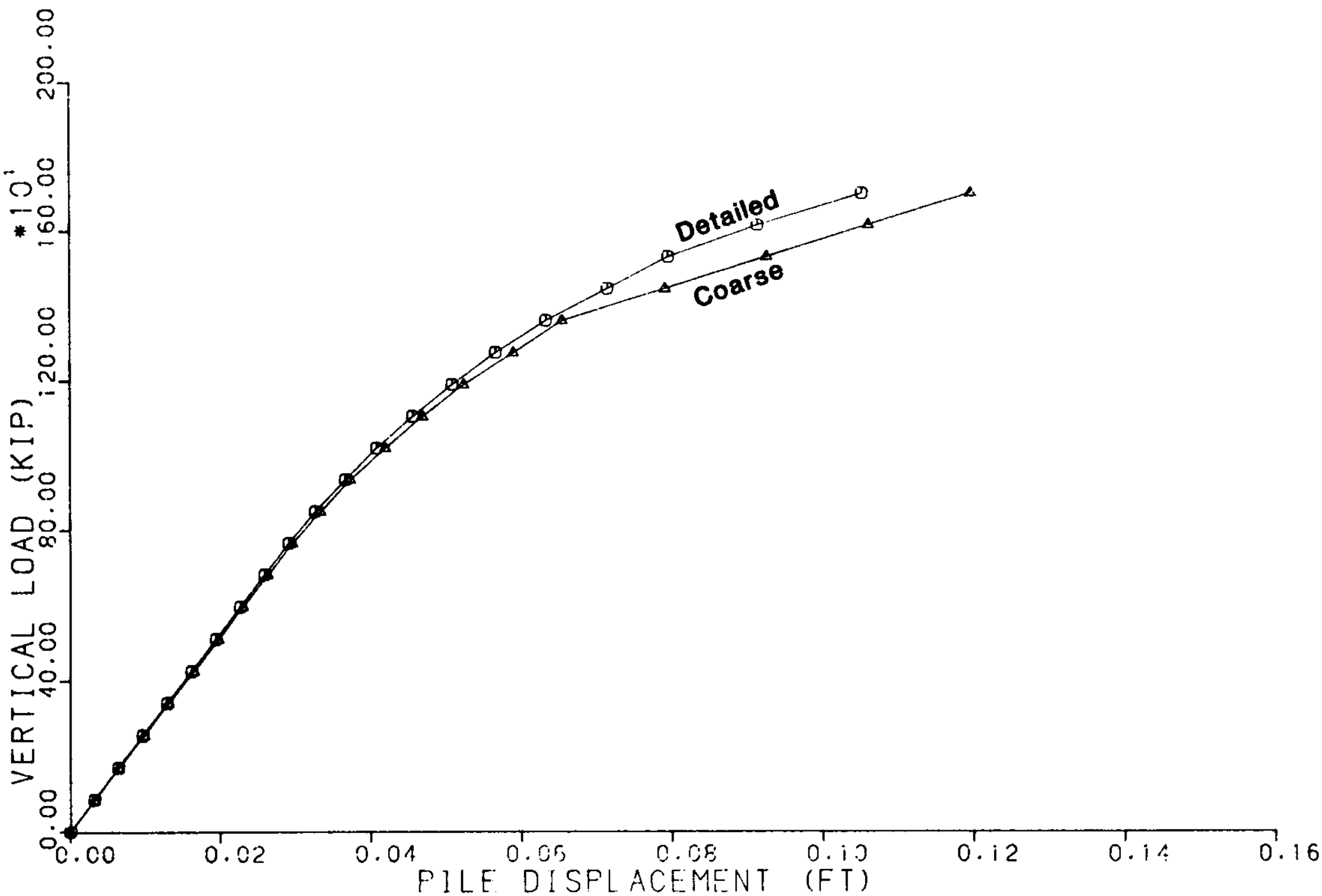
Depth	S_u	ϵ_{50}	γ_i
0′	1400 psf	0.5%	50 pcf
6′	500 psf	0.5%	60 pcf
20′	1200 psf	0.5%	60 pcf
50′	2000 psf	0.5%	60 pcf
70′	1500 psf	0.5%	60 pcf
120′	ϕ = 40 deg.	0.5%	60 pcf
170′	ϕ = 40 deg.	0.5%	60 pcf

Piles (Welded)

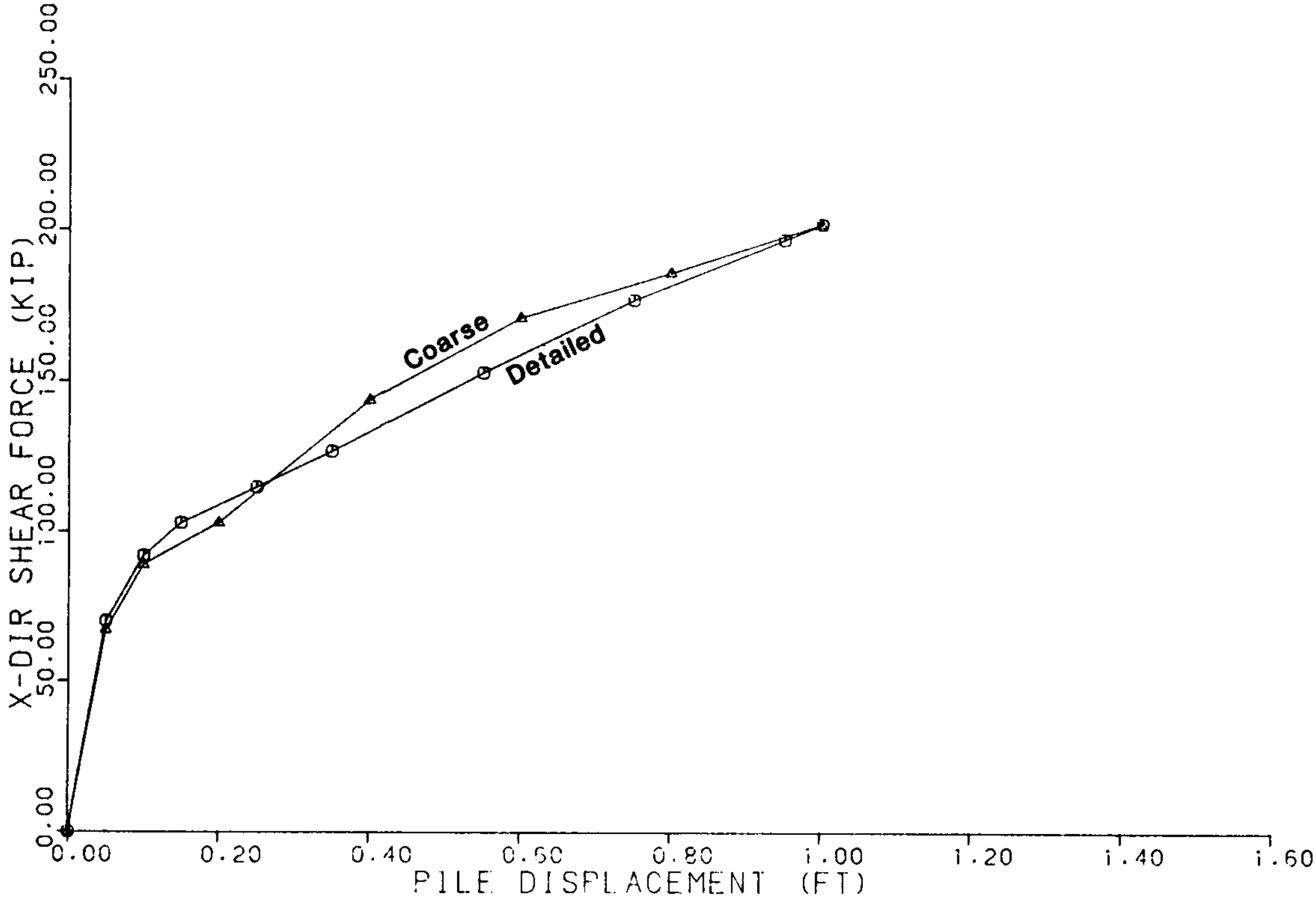
8 Total
125′ Penetration
30" ϕ with 5/8" Wall Thickness
σ_y = 45 ksi

Conductors

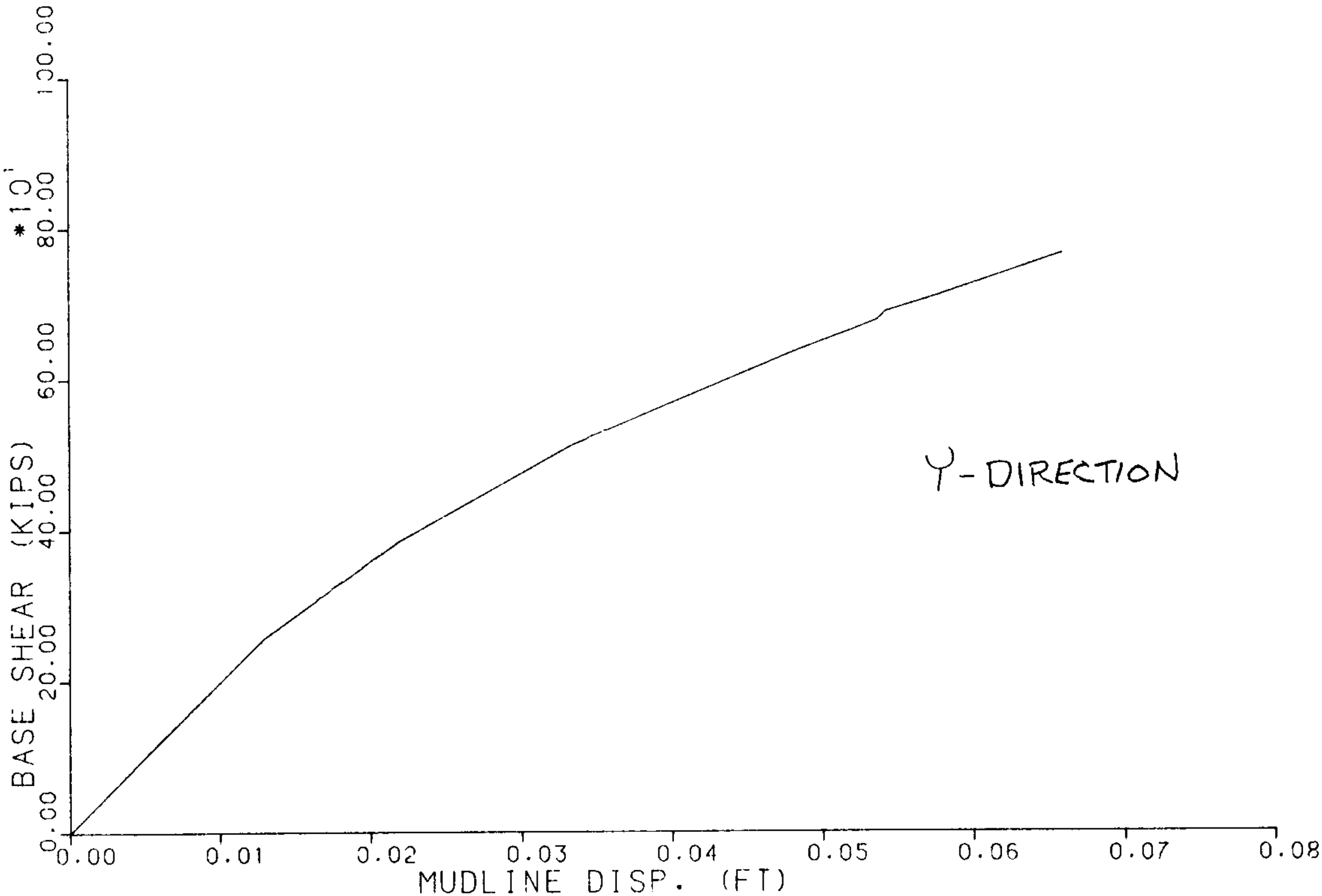
5 inside - 30 ϕ with 5/8" Wall Thickness
2 outside/braced - 20" ϕ with .593" Wall Thickness
σ_y = 45 ksi



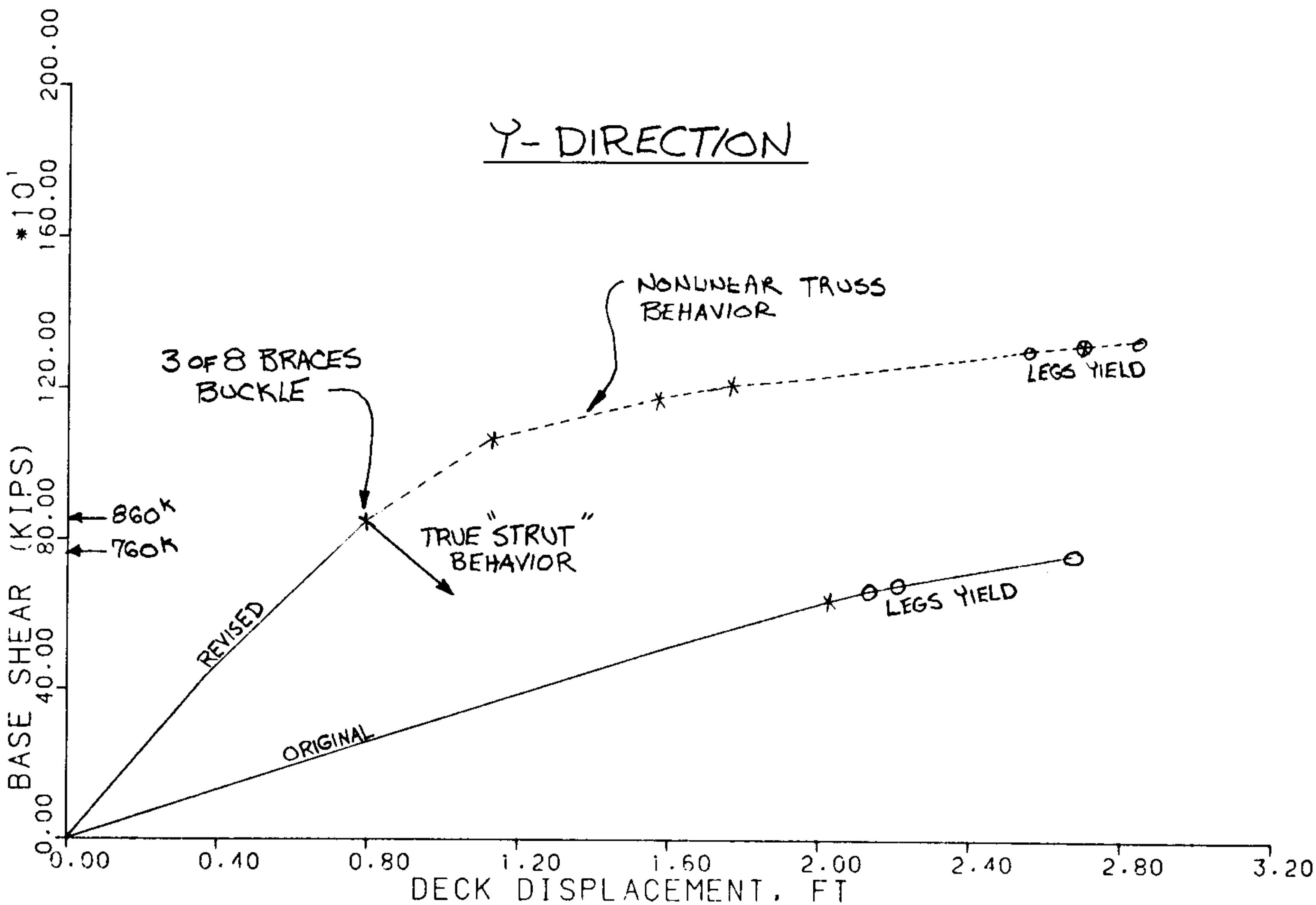
PLATFORM "B". SINGLE PILE RESPONSE TO Z-DIR.LOAD



PLATFORM "B", SINGLE PILE RESPONSE TO X-DIR LOAD



PLATFORM "B" LOAD-DISPLACEMENT CURVE, Y-WAVES.



PLATFORM "B" LOAD-DISPLACEMENT CURVE, Y-WAVES.

APPENDIX C

COMPUTER MODELING

APPENDIX C

PLATFORM "C" EVALUATION

Page	Description
C.1	Key characteristics concerning the computer modeling and analysis. Note the analysis was conducted in a static rather than dynamic "pseudo-static" mode. The dynamic method is more difficult to understand and implement but handles "buckling" members (struts) much better than the static method. Buckling members are difficult to handle with static analysis. Therefore, for the purposes of this study nonlinear truss elements were used instead of buckling elements for the static pushover analysis..
C.2	Miscellaneous analysis conditions. Note in particular the 25 percent increase in F_y to account for the adjustment of nominal to near yield values and strain rate effects.
C.3 - C.4	Hydrodynamic and aerodynamic force equations and related coefficients.
C.5 - C.6	Element modeling for Platforms A and B.
C.7	PSAS (Pile-Soil-Analysis-System) element response. The degraded soil condition was used without any strain rate effects.
C.8	Typical brace or "strut" response curve. Due to the difficulties in handling these elements in a static analysis (as noted above), a nonlinear truss element was used which does not "shed" load after failure but instead remains perfectly plastic (page C.8). The use of a nonlinear truss element in lieu of a strut element does not appear to substantially affect the results of this study. Ongoing modifications to SEASTAR will allow for a static analysis with strut elements.
C.9	Nonlinear truss element. The element was set to be initially elastic and then plastic at the failure load.
C.10	Comparison between nonlinear truss and strut element for a typical platform member from this study.

COMPUTER MODELING

- PMB Program SEASTAR
- Full 3-D Nonlinear Model
- Static Pushover Analysis
- Soil/Pile - PSAS (Pile Soil Analysis System)
- Braces - Struts/NTRUSS (Buckling, Punching)
- Piles/Legs/Conductors - Nonlinear Beams
- Deck Elements - Linear Beams

HYDRODYNAMIC FORCES

- Compute Wave Kinematics:

  Use Stream Function wave theory [15] to determine water particle velocities and accelerations.

- Compute Hydrodynamic Force:

$$F_H = C_D \cdot \frac{w}{2g} \cdot A.\ u\ u + C_M \cdot \frac{w}{g} \cdot Vol.\ a$$

where

C_D = drag coefficient (ft^2)
- For tubular members, use $C_D = 0.7$. Use $C_{DR} = 1.0$ for members roughened by marine growth.
- For long flat plates, I-beams and box sections in the deck, use CD = 2.0. See Table B.2 in [16].
- For deck equipment, the value of C_D should be reduced from 2.0 by a factor depending on the aspect ratio given in Table B.3 in [16].

C_M = inertia coefficient = 1.5
A = area of element (member) (ft^2)
u = wave velocity component normal to element (ft/sec)
Vol = volume of element (member) (ft^3)
a = wave acceleration component normal to element (ft/sec/sec)
F_H = hydrodynamic force (lb)

For conditions where the wave crest is in the decks, use the projected frontal area and volume of the deck elements subjected to hydrodynamic forces.

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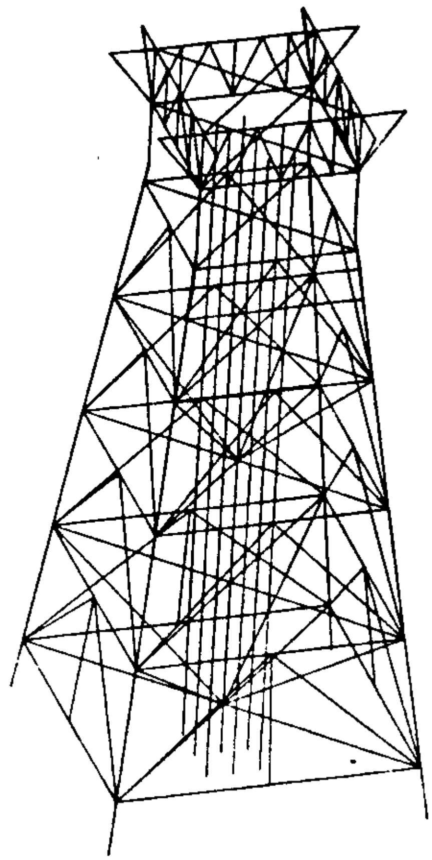

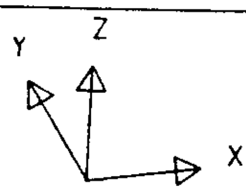

GLOBAL AXES

140'W/D PLATFORM "A"

GENERAL VIEW OF THE STRUCTURE

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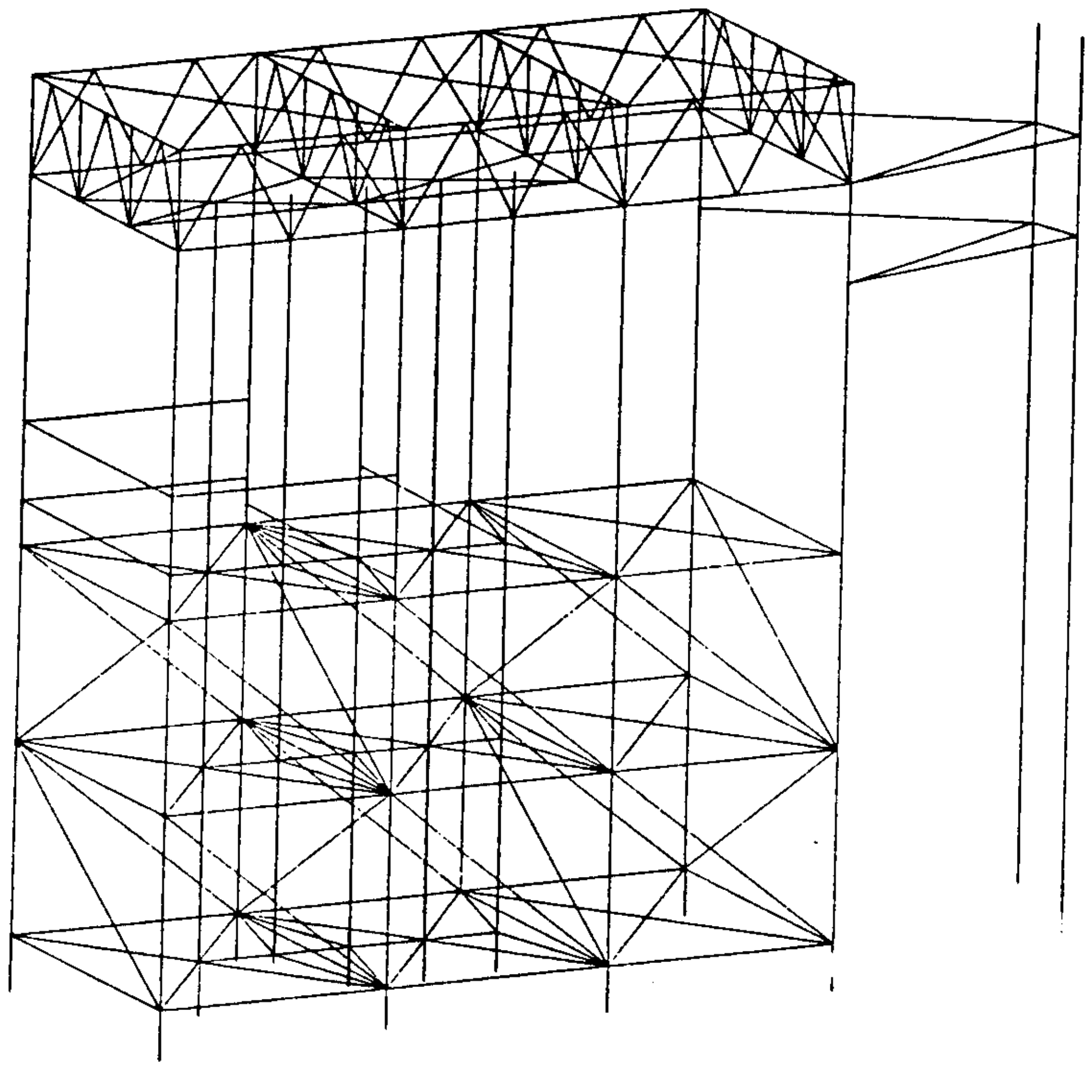

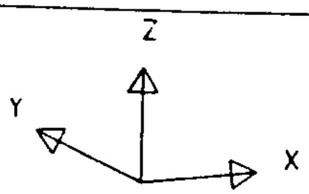

GLOBAL AXES

AIM 2. B PLATFORM

PLATFORM ISOMETRIC VIEW

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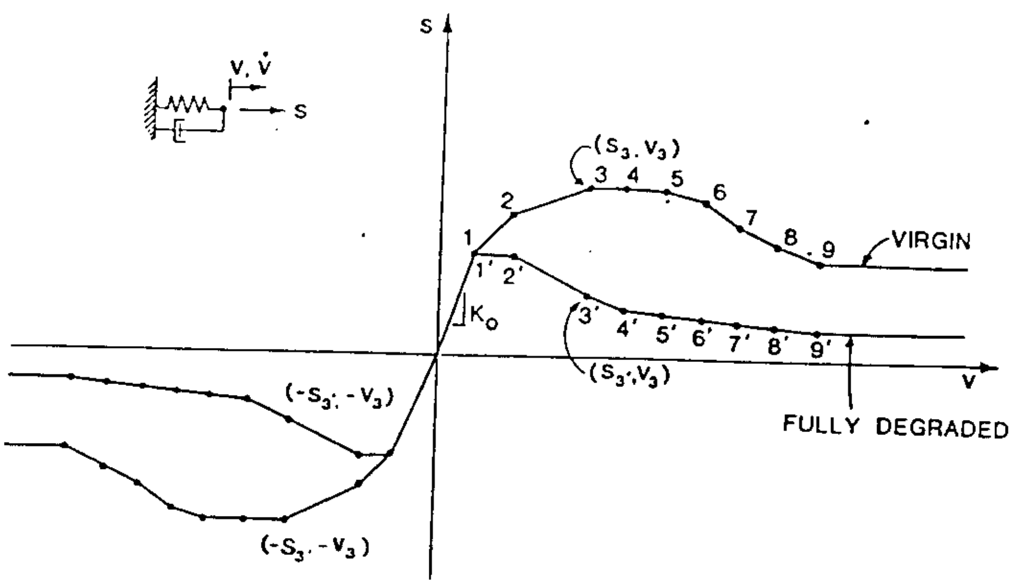
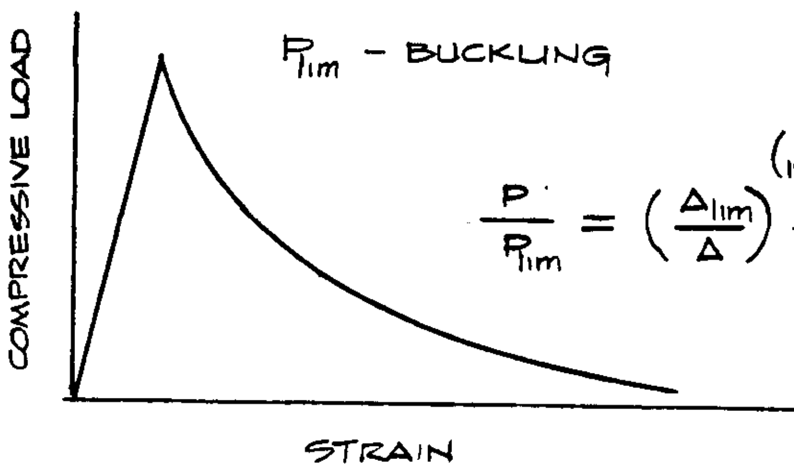


Typical PSAS Backbone Curve

(REF OTC 4806, 1984)

MARSHALL STRUT DEVELOPMENT

(MARSHALL, OTC 2908, 1977)



$$\frac{P}{P_{lim}} = \left(\frac{\Delta_{lim}}{\Delta}\right)^{\left(\frac{Kl}{120r}\right)}$$ — POST BUCKLING BEHAVIOR

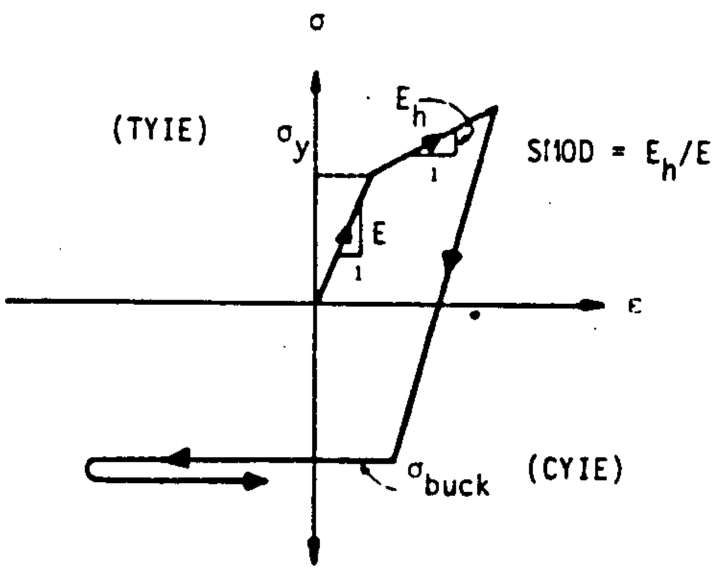
$$\frac{1}{1-\frac{P_{lim}}{P_{eb}}}\,\frac{M}{M_p} = \cos\left(\frac{\pi}{2}\,\frac{P_{lim}}{P_{cr}}\right)$$

M = ACTING MOMENT FROM LATERAL LOADS

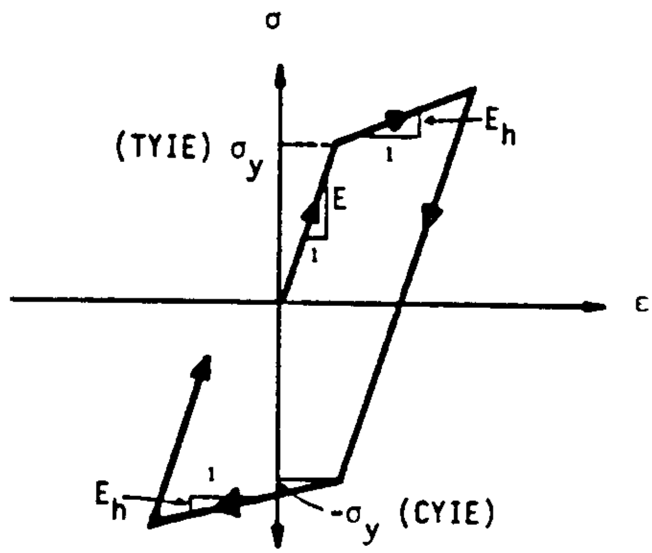
M_p = PLASTIC MOMENT CAPACITY.

P_{cr} = CENTRALLY LOADED COLUMN STRENGTH (PER CRC EQUATIONS)

P_{eb} = EULER LOAD

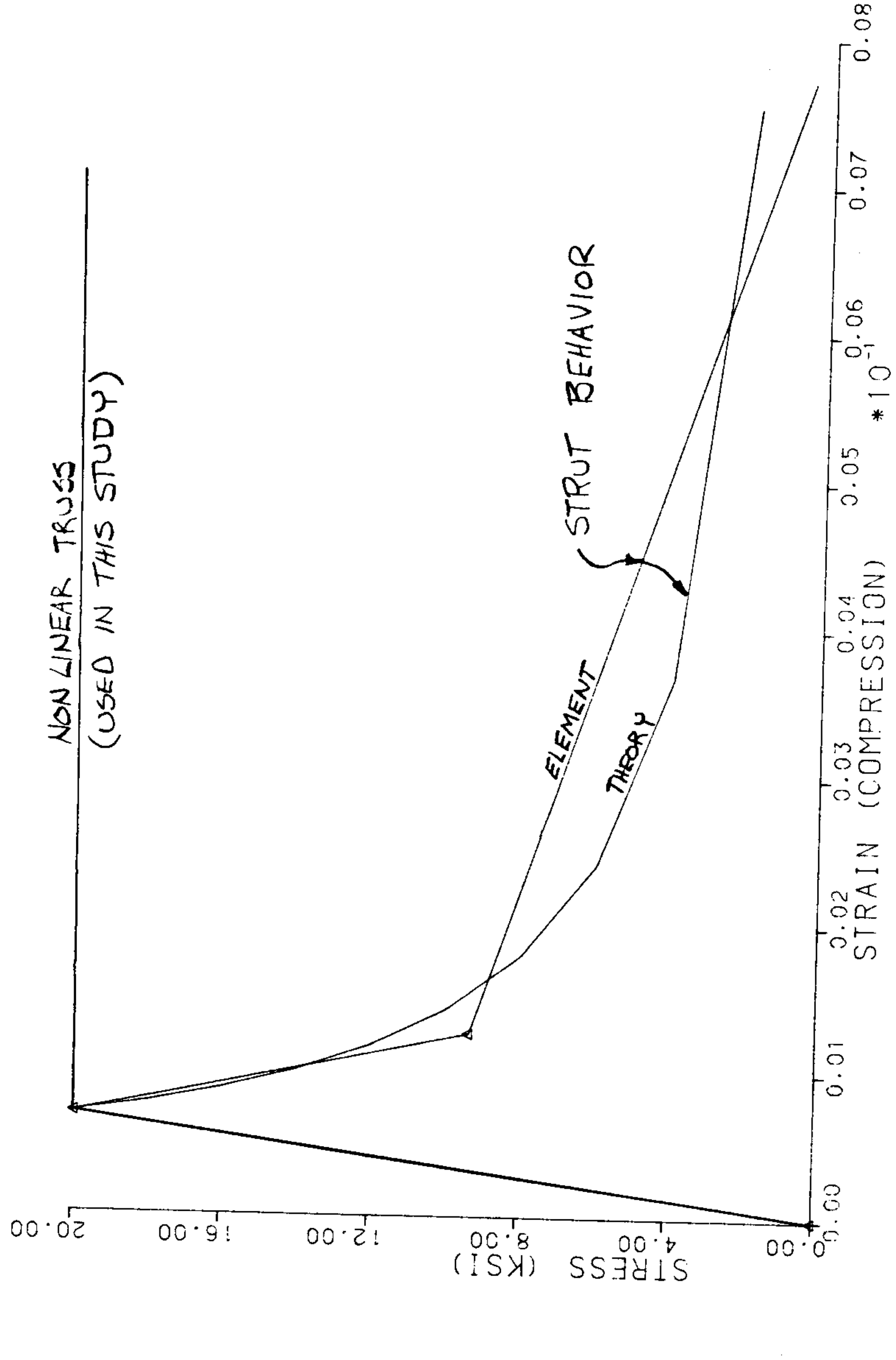


(a) Elastic buckling in compression



(b) Compression and Tension Yield

NTRS Stress-Strain Relationship



MATERIAL CURVE FOR MARSHALL STRUT - 301 PLAT A

STRUT

STRUT BEHAVIOR CONTROLLED BY:

- MEMBER PROPERTIES (d, t, L)
- LATERAL LOADING FROM WAVES
- JOINT PUNCHING AT LEG

JOINT CAPACITY

- Equations Based on Brace Member Loads

- API RP 2A 17th Edition, May 1987
  (without 1.7 Joint Safety Factor)

Lower Bound

$\uparrow$

Δ = 10 *to* 40%

$\downarrow$

Median

- UEG - "Design Tubular Joints for
  Offshore Platforms" 1985

JOINT PUNCHING SHEAR
UEG EQUATIONS - AXIAL LOADS
REFLECT "MEAN" BOUND OF TEST DATA

("Design of Tubular Joints for Offshore Platforms," UEG 1985 and Billington, et al., OTC 4189, 1982)

COMPRESSION

$$P_a = \frac{F_y T^2}{\sin\theta}(4.1 + 20.3\beta) F_l Q'_\beta K$$

Where

F_y = **chord yield stress**

T = **chord wall thickness**

θ = **Angle between brace and chord**

β = **diameter ratio = brace/chord = d/D**

F_l = **intersection length factor**

$\cong (1 + 1/\sin\theta)/2$

Q'_β = **geometric modifier**

$= 1.0 \quad for \quad \beta \leq 0.6$

$= \dfrac{0.3}{\beta(1-0.8\ 3\beta)} \quad for \quad \beta \geq 0.6$

K = o **T & Y Joints** **K** = 1.0

o **K & YT Joints** **K** = $1.0 for \zeta \geq 0.15$

K = $1.9-6\zeta \leq for \zeta \leq 0.15$

ζ = **gap parameter**

= **gap length (Lg)/D**

o **X & DT** **K** = 0.75

JOINT PUNCHING SHEAR (Cont.)

TENSION

General Equation:

- Y & T Joints   2.15 * Compression P_a
  DT Joints
- K & YT & X   No test data available

  Therefore, use Compression Results

GROUTED LEG JOINTS

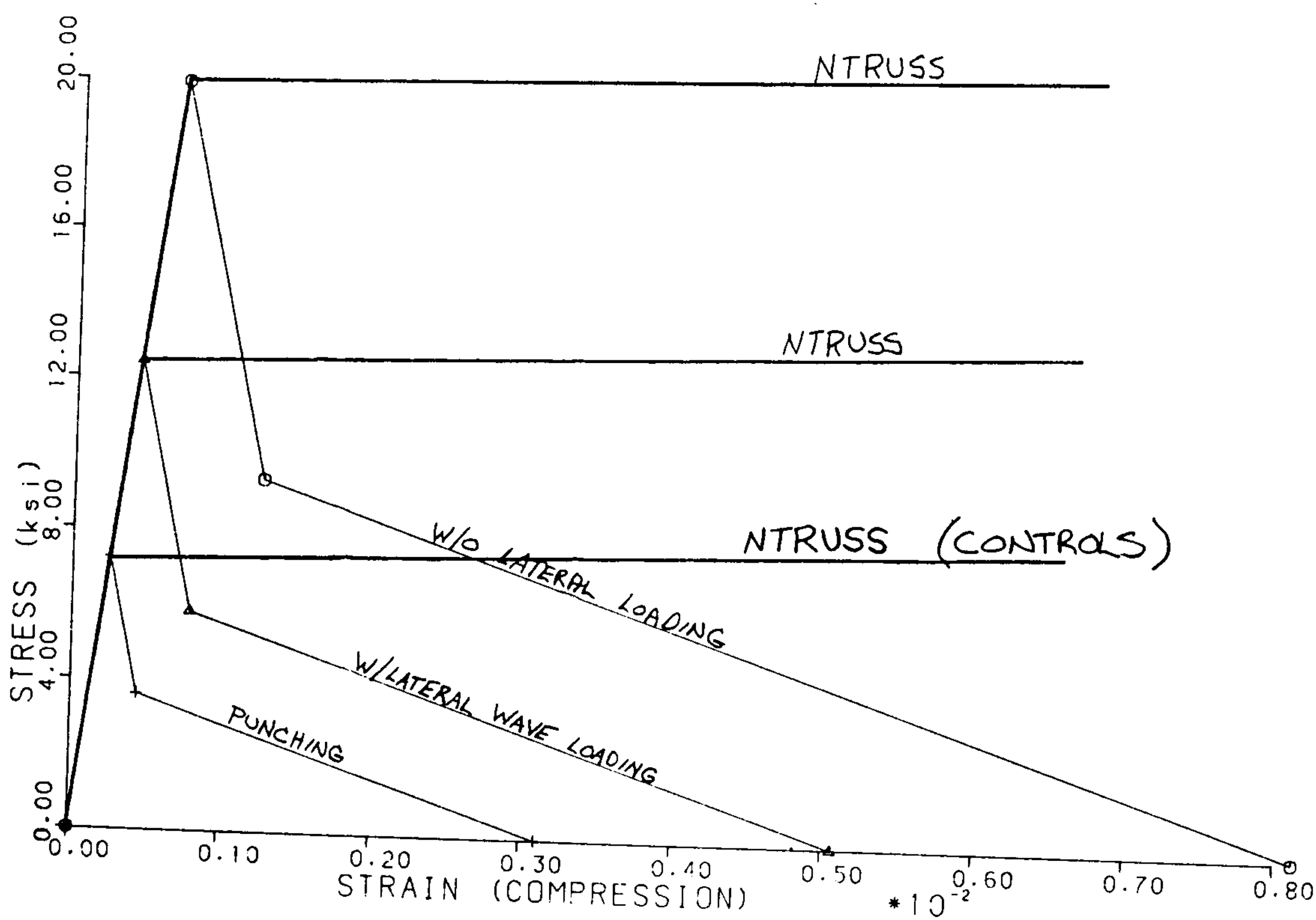
- Increased Compression Capacity
- Equivalent Chord Wall Thickness

$$T_{eff} = \sqrt{\frac{T^3 + T_p^3}{T}} \geq 2T$$

Where

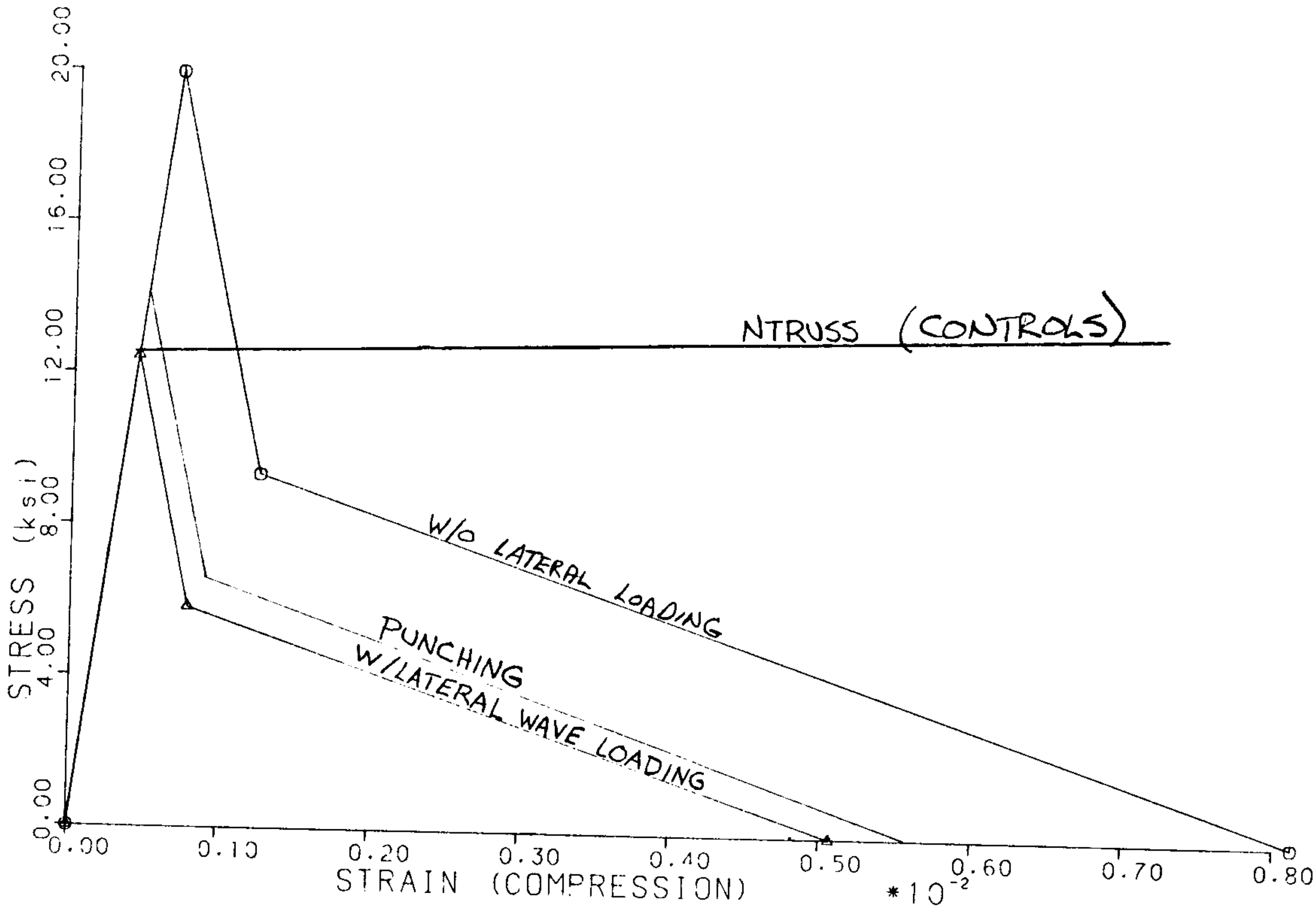
T = Leg Thickness

T_p = Pile Thickness



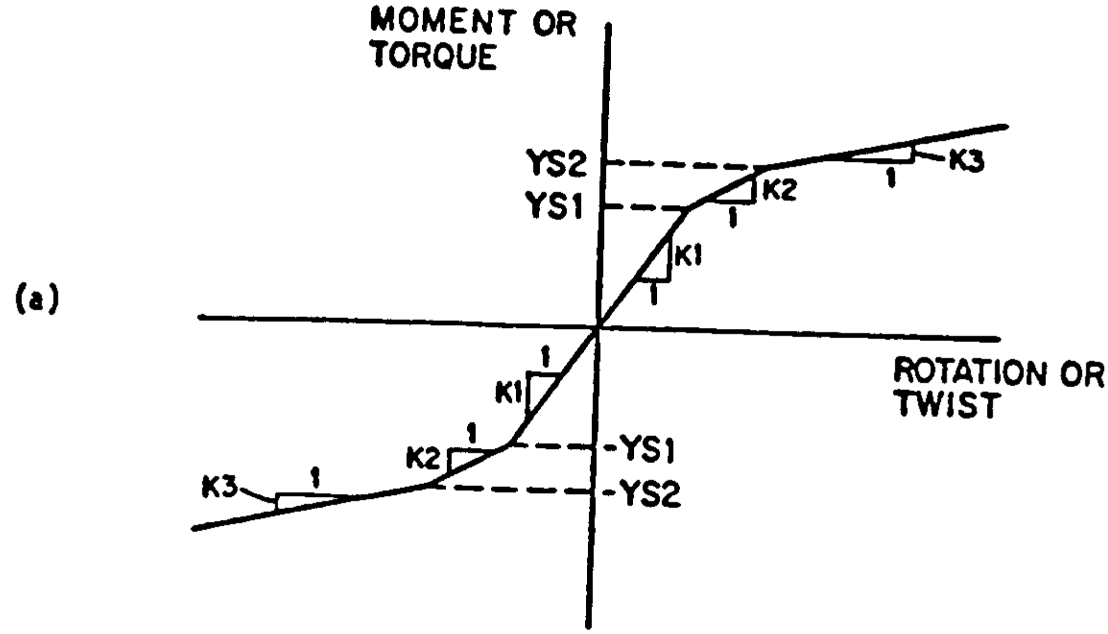
MATERIAL CURVE FOR MARSHALL STRUT ELEMENT 301

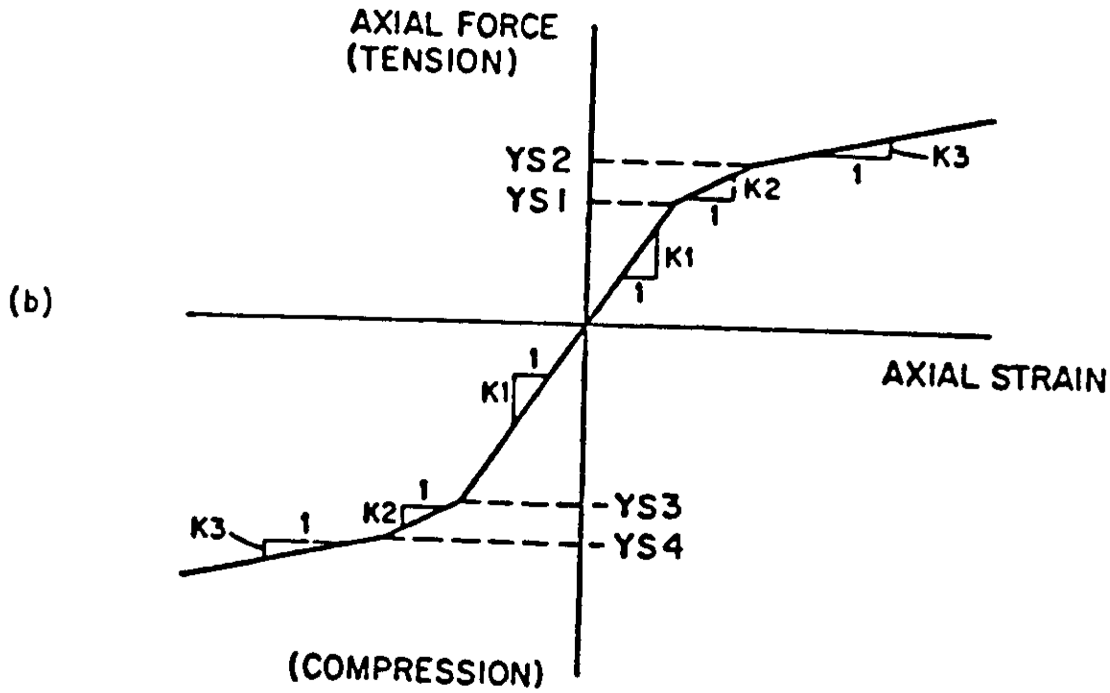
PLATFORM "A"



MATERIAL CURVE FOR MARSHALL STRUT

PLATFORM "B"





NONLINEAR BEAM-COLUMN ACTION-DEFORMATION RELATIONSHIPS

DAMAGED MEMBER CAPACITY

1. **MISSING MEMBER - Eliminate member**

2. **COMPLETELY SEPARATED MEMBER - Eliminate member**

3. **CRACKED MEMBER**

   - **Assume all cracks are through cracks**

   - **Adjust brace strength as follows:**

$$P_{cracked} = P_{ult}\left(\frac{L_{crack}}{L_{circum}}\right)$$

   - **Adjust similarly for post-buckling behavior**

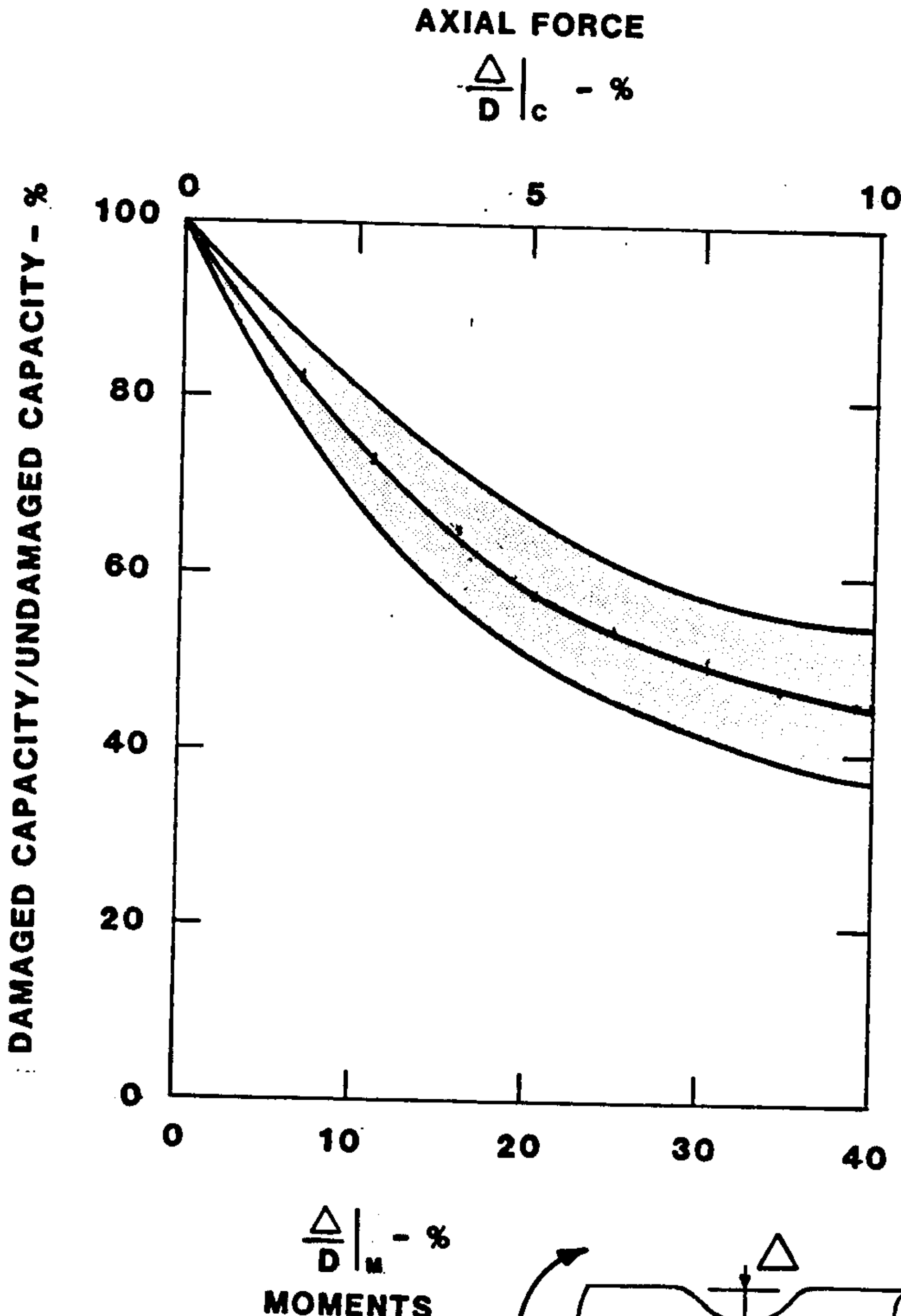
4. **DENTED MEMBER**

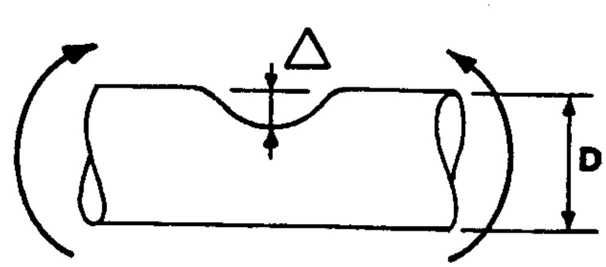
   - **Adjust brace capacity according to Figure 4-20 AIM-I report** (PAGE C.17)

   - **Use mean values**

   - **Adjust similarly for post-buckling behavior**

DAMAGED BRACE CAPACITY

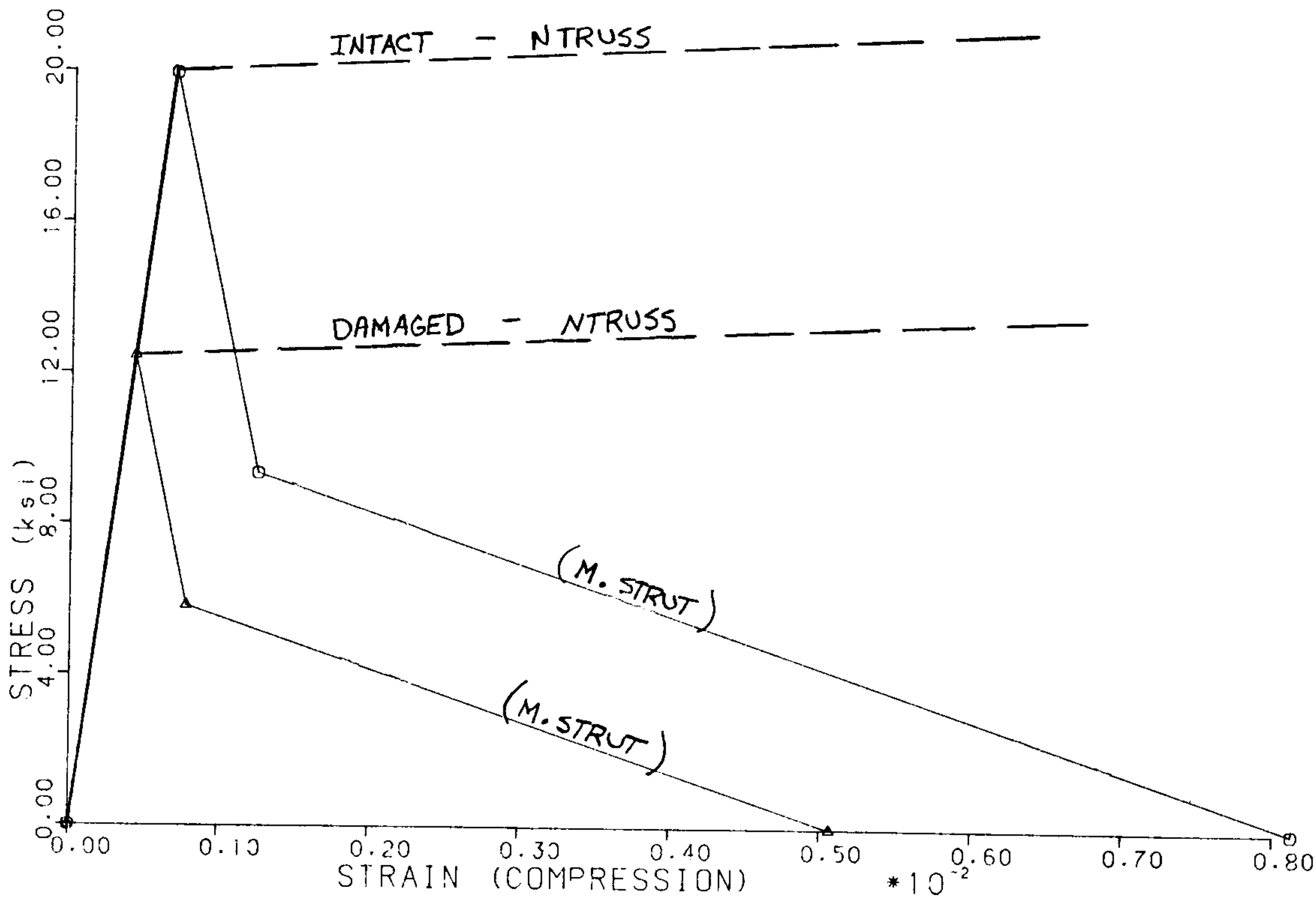




$40 \leq D/t \leq 60$
$60 \leq L/r \leq 80$

(AFTER TABY & MOAN
BOSS '85)

FIG. 4-20
(AIM I REPORT)



MATERIAL CURVE FOR MARSHALL STRUT ELEMENT 301

APPENDIX D

COST DATA BACKGROUND

APPENDIX D

PLATFORM "D" EVALUATION

Page	Description
D.1 - D.2	Repair cost summaries for Platforms A and B. Individual item costs are based upon data shown on pages D.3 to D.8. No discount has been taken for completing all of the work at one time.
D.3	General repair cost summary for fixing a variety of platform problems at a 50′ water depth and a 150′ water depth. Costs are based upon the detailed sheets shown on pages D.4 to D.8.
D.4 - D.8	Itemized costs and schedule for each repair scheme indicated on page D.3.
D.9	Costs for raising the deck elevation for a 50′ water depth site (Platform B) and a 150′ water depth site (Platform A).
D.10	Cost background and schedule for strengthening Platform A by grouting the pile to the legs.
D.11	Cost background and schedule for reducing hydrodynamic loads on Platform B by removing 2 (of 3) boat landings and removing marine growth.
D.12	Inspection costs for a 50′ W.D. (Platform B) and a 150′ W.D. (Platform A). Three types of inspections and associated cost ranges are provided.
D.13	Detailed restoration and replacement costs for Platform A.
D.14	Detailed restoration and replacement costs for Platform B.
D.15 - D.16	Detailed AIM cost calculations for Platform A for indicated conditions.
D.17 - D.18	Detailed AIM cost calculations for Platform B for indicated conditions.

PLATFORM "A"

DAMAGE REPORT SUMMARY

ITEM NO.	LOCATION	DAMAGE	REPAIR COSTS
1	Vertical Interior Diagonal B2 at -27.5′ to Center Leg at -65′	Missing	$250K
2	Vertical Interior Diagonal B1 at -27.5′ to Center Leg at -65′	Completely Separated from Leg at B1	$300K
3	Vertical Face Diagonal, Row B Midpoint B1 to B2 at -27.5′ to B1 at -65′	Completely Separated from Horizontal Member B1 to B2 at -27.5′	$250K
4	Vertical Face Diagonal, Row B Midpoint B1 to B2 at -65′ to B1 at -102.5′	Completely Separated from Horizontal Member B1 to B2 at -65′	$300K
5	Vertical Interior Diagonal A2 at -27.5′ to Center Leg at -65′	Cracked at A2 from 12:00 to 5:00 Crack Length = 40"	$40K
6	Horizontal Interior Diagonal -65′ B2 to Center Leg	Cracked at B2 from 9:30 to 2:30 Crack Length = 14"	$40K
7	Horizontal Interior Diagonal -28′ B2 to Center Leg	Cracked at B2 from 4:00 to 8:30 Crack Length = 12.75"	$25K
8	Horizontal Interior Diagonal -28" A2 to Center Leg	Cracked at A2 at 4:30 Crack Length = 12.5"	$25K
9	Horizontal Face Member Row B B1 to B2 at -65′	Cracked at B2 at 3:00, 5:00, 9:00 Crack Length = 7.25" Total	$40K

TOTAL REPAIR COST = $1.3 M

P.1

PLATFORM "B"

DAMAGE REPORT SUMMARY

ITEM NO.	LOCATION	DAMAGE	
1	Horizontal Face Member Row B B2 to B3 at -4'	Complete Separated from Leg at B2 Numerous Dents	REPAIR COSTS 200^k
2	Horizontal Interior Diagonal -4' B3 to A2	Cracked at B3 from 11:30 to 4:30 Crack Length = 20"	30^k
3	Horizontal Face Member Row B B4 to B3 at -4'	Dent 56" x 11" x 2" Deep 4" Crack on Bottom of Dent	30^k
4	Horizontal Face Member Row A A3 to A4 at -4'	Dent 10" x 8" x 1/2" Deep	30^k

TOTAL REPAIR COST = 290^k

REPAIR COST SUMMARY

Repair Scheme		Duration	Costs ($1000)	
No.	Description	(Days)	50 Ft. W.D.	150 Ft. W.D.
1A	Remove/Replace 14"	10 - 14	178 - 248	222 - 310
1B	Replace 14"	10 - 14	178 - 248	222 - 310
2A	Add Doubler (14")	3	33	46
2B	Add Doubler (53")	5	69	91
3	Add Pipe Stub	8	98	134
4	Replace Node	10 - 14	178 - 248	222 - 310
5	Replace Anode	1	18	31

Repair Schemes 1A and 1B

Remove Existing Damaged Brace

Add Replacement Brace

14" dia. x 375"; L = 40 ft.

Depth = 50 ft.

Cost Data

Vessel:	Jackup @ $3000/Day	
Diving Spread:	$14,000/day	20 Men @ $400/day/ea Equipment - Hyperbaric Welding
Misc:	$500/day Consumables	
Construct. Mat'l:	$2500 (14" dia. x 40' Leg + Doublers (9 ft^2)	

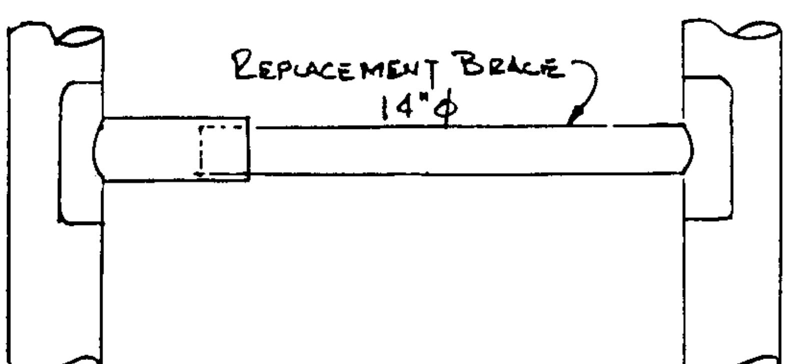
Schedule

3 Days Brace Removal
11 Days Replacement and Inspection

14 Days for 1A   12 days for 1B

Total Cost

14 day	$247,500
10 day	$177,500



Repair Scheme 2A

Doubler Addition to Dented Brace

1 Piece; 180 degrees; L = 10 ft.; Size = ½" x 14" ID

Depth = 50 ft.

Cost Data

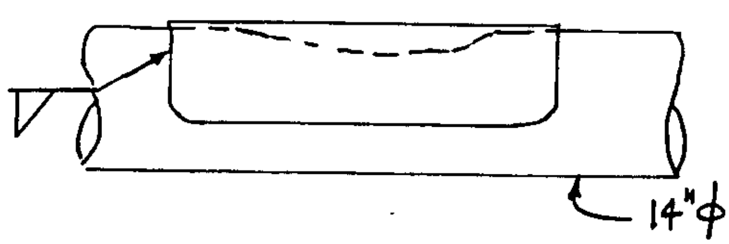
Vessel:	Jackup @ $3000/Day	
Diving Spread:	$7,000/day	12 Men @ $400/day/ea Equipment - Wet Weld
Misc:	$500/day Consumables	
Construct. Mat'l:	$1000	

Schedule

3 Days

Total Cost

$32,500



Repair Scheme 3

Insert 12-3/4" Diam. x .500" WT Pipe Stub

L = 10 ft.

Depth = 50 ft.

Cost Data

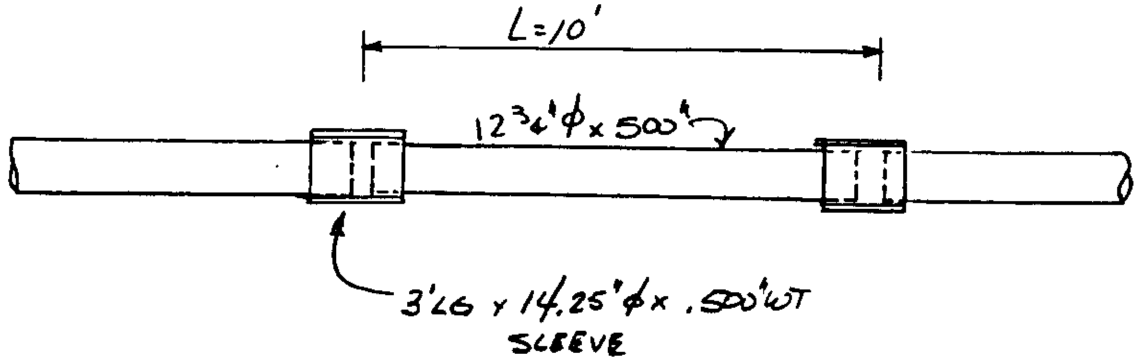
Vessel:	Jackup @ $3000/Day	
Diving Spread:	$8,500/day	12 Men @ $400/day/ea Equipment
Misc:	$500/day Consumables	
Construct. Mat'l:	$2000	12-3/4" x 10' 14-1/4" x 6'

Schedule

8 Days

Total Cost

$98,000



Repair Scheme 4

Replace K Node

Remove Damaged Braces

Add Prefabricated Node with Sleeves
(14" diam. Chord, L = 10′, 12" Diag, L = 4′)

Habitat Weld

50′ W.D.

Cost Data

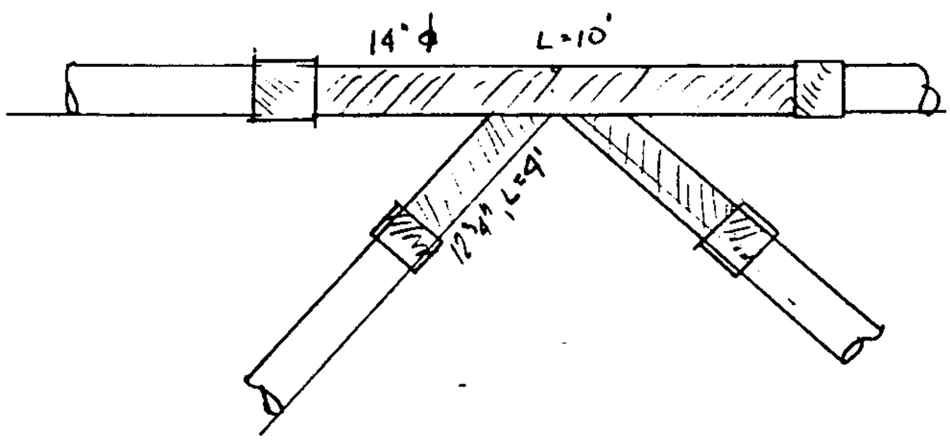
Vessel:	$3000/Day	
Diving Spread:	$14,000/day	
Misc:	$500/day Consumables	
Construct. Mat'l:	$2500	14" x 10′
		12" x 8′
		Sleeves

Schedule

Remove Damage	2 days
Add Replacement	10 days
Inspection	2 days
	14 days

Total Cost

$247,500	14 days
$177,500	10 days



Repair Scheme 5

Add 325# Anode

Depth = 50 ft.

Wet Weld

Cost Data

Vessel:	Jacket @ $3000/Day	
Diving Spread:	$7,000/day	10 men @ $400/day Equipment
Misc:	$500/day Consumables $1000 Anode + Stiff PL	

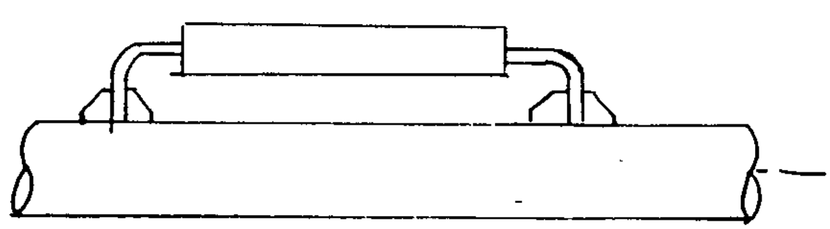
Schedule

1 Day Divers +
Mob/Demob @ 2

3 Days Vessel Only

Total Cost

$17,500



PLATFORM REPAIR

RAISE DECK ELEVATION

		Duration		Total Cost($1000)	
No.	Activity	50′	150′	50′	150′
1	Engineering	--	--	100	100
2	Operations Prelift	7	10	70	83 - 160(1)
3	Lift	7	6	521.5	126 - 360(2)
4	Hookup/Startup	17	20	170	161 - 320(1)
5	Fabrication	--	--	83	70
	TOTAL	31	36	944.5	540 - 1,010

(1) Assumes Temporary Quarters Set On Platform (Low Side) Or Jacket Work Vessel (High Side)

(2) Assumes 500T Stiff Leg (Low) Or 1200T Derrick Barge (High)

(Costs Assume Well Heads Relocated to Cellar Deck)

PLATFORM A

"REPAIR" BY GROUTING LEGS

Option: Grout 4 legs in 160 ft. W.D. Using Pressure Grout Method.

Scheme:

- Secure Pressure Grout Consultant and Patent License
- Add 2 Grout/Air Connections to Each Leg
- Mobilize Grout Spread
- Pressure Grout Legs

Costs:	Consultant/Licensee	$ 15,000	(est.)
	Grout/Air Connections	$ 5,000	
	Grout Job (including equipment and materials)	$ 30,000	
	TOTAL	$ 50,000	

Schedule:	Make Connections	2 days
	Grout Job	1 day
	TOTAL	3 days

PLATFORM B

Boat Landing Removal

		Cost/Day ($)			
Activity	Duration	Vessel	Crew	Misc.	Total Cost
Mob/Demob	2/1	3000	5000	---	$11,000
Remove	2	3000	5000	250	$16,000
Transport & Offload	2	1000	1000	---	$ 3,000
				TOTAL	$20,500

Marine Growth Removal

		Cost/Day ($)			
Activity	Duration	Vessel	Crew	Misc.	Total Cost
Mob/Demob	2/1	3000	4000	---	$19,000
Water Blast	5	3000	4000	1000	$40,000
				TOTAL	$59,000

AIM II

PLATFORM INSPECTIONS

		Costs ($1000)	
No.	**Description**	**50' W.D. 8 Pile**	**150' W.D. 4 Pile**
1	Visual Diver Check Missing Members Debris, Scour	$3 (1 day)	$4 (1 day)
2	Intermediate Visual Check Clean and Check Key Joints Check Cathodic Potential	$9 - $12 (3 to 5 days)	$15 - $20 (3 - 5 days)
3	Extensive Visual, Cathodic Potential Clean All Joints UT, MPI	$24 - $35 (6 to 8 Days)	$40 - $70 (7 to 12 days)

PLATFORM A

FAILURE COSTS

RESTORATION COSTS

Salvage	$ 1,000,000	
Plug and Abandon 9 Wells	500,000	(Mob/demob)
	1,800,000	P & A - 9 x $200,000/ea
TOTAL COST	$ 3,300,000	

REPLACEMENT COSTS

Jacket	400 T @ 1250	$ 500,000
Deck	400 T @ 1750	$ 700,000
Piling	575 T @ 750	$ 431,000
Equip	(w/o Quotes)	$ 1,825,000
Install	11 days @ 50,000	$ 550,000
Contingency	10 percent	$ 400,000
		$ 4,400,000
Redrill Wells	2.5M/ea x 9	$22,500,000
TOTAL COST		$26,900,000

PLATFORM B

FAILURE COSTS

RESTORATION COSTS

Salvage	$ 500,000	
Plug and Abandon 5 Wells	500,000	(Mob/demob)
	1,000,000	P & A - 5 x $200,000/ea
TOTAL COST	$ 2,000,000	

REPLACEMENT COSTS

Jacket	300 T @ 1250	$ 375,000
Deck	500 T @ 1750	$ 875,000
Piling	500 T @ 750	$ 431,000
Equip	(w/o Quotes)	$ 1,160,000
Install	14 days @ 50,000	$ 700,000
Contingency	10 percent	$ 348,000
		$ 4,700,000
Redrill Wells	2.5M/ea x 5	$12,500,000
TOTAL COST		$17,200,000

PLATFORM A

AIM COST CALCULATIONS

$$E(C) = E(I) + E(F)$$

Conditions:

- 12-Year Remaining Life
- Platform Replacement
- $C_D = 0.7$

Alternative 1: Do Nothing			
E(I):	.40 M		
E(F):	- Platform Capacity (Damaged Curve)	=	948 k
	- Return Period	=	42 Years
	- Cost = 3.3 + 26.9	=	30.2 M
E(C) =	.40 + (1/42) x 30.2 x 12		
E(C) =	.40 + 8.63	=	9.03 M

Alternative 2: Repair			
E(I):	1.7 M		
E(F):	- Platform Capacity (Repaired Curve)	=	1060 k
	- Return Period	=	45 Years
	- Cost	=	30.2 M
E(C) =	1.7 + (1/45) x 30.2 x 12		
E(C) =	1.7 + 8.05	=	9.75 M

PLATFORM A

AIM COST CALCULATIONS (Cont.)

$$E(C) = E(I) + E(F)$$

Alternative 3: Repair and Grout			
E(I):	1.75M		
E(F):	- Platform Capacity (Repair and Grout Curve)	=	1155 k
	- Return Period	=	50 Years
	- Cost	=	30.2 M
E(C) =	1.75 + (1/50) x 30.2 x 12		
E(C) =	1.75+ 7.25	=	9.00 M

Alternative 4: Repair and Raise Deck			
E(I):	2.70 M		
E(F):	- Platform Capacity (Raise Deck Curve)	=	1440 k
	- Return Period	=	180 Years
	- Cost	=	30.2 M
E(C) =	2.7 + (1/180) x 30.2 x 12		
E(C) =	2.70 + 2.01	=	4.71 M

PLATFORM B

AIM COST CALCULATIONS

$$E(C) = E(I) + E(F)$$

Conditions:

- 5-Year Remaining Life
- Platform Replacement
- C_D = 0.7
- Maximum Breaking Wave (46′)
  Return Period = 275 Yr.

Alternative 1: Do Nothing			
E(I):	0.15 M		
E(F):	- Platform Capacity (Damaged Curve)		X = 1135 k Y = 760 k N = 1000+ k
	- Return Period		X = 115 Yr Y = 12 Yr N = 10000+ Yr
	- Cost	=	19.2 M
E(C) =	0.15 + (1/12 - 1/275) x 19.2 x 5		
E(C) =	0.15 + 7.67	=	$7.80 M

Alternative 2: Remove Boat Landings and Marine Growth			
E(I):	0.35 M		
E(F):	- Platform Capacity	=	760 (Y)
	- Return Period	=	20 Yr (Y)
	- Cost	=	19.2 M
E(C) =	0.35 + (1/20 - 1/275) x 19.2 x 5		
E(C) =	0.35 + 4.45	=	$4.80 M

PLATFORM B

AIM COST CALCULATIONS (Cont.)

$$E(C) = E(I) + E(F)$$

Alternative 3: Repair Elements

E(I):	0.45M		
E(F):	- Platform Capacity	=	760 k (Y)
	- Return Period	=	12 Yr (Y)
	- Cost	=	19.2 M
E(C) =	0.45 + (1/12 - 1/275) x 19.2 x 5		
E(C) =	0.45 + 7.67	=	8.12 M

Alternative 4: Repair and Raise Deck

E(I):	1.45 M		
E(F):	- Platform Capacity	=	760 k (Y)
	- Return Period	=	12 Yr (Y)
	- Cost	=	19.2 M
E(C) =	1.45 + (1/12 - 1/275) x 19.2 x 5		
E(C) =	1.45 + 7.67	=	9.12 M

APPENDIX E

REVIEWS OF AIM-II PROJECT BY

G. C. LEE AND B. C. GERWICK

038318

GRIFF C. LEE, INC.

P.O. BOX 70787, NEW ORLEANS, LA. 70172 (504) 587-6512
(504) 282-3367

August 10, 1987

Mr. R. G. Bea
PMB Systems Engineering Inc.
500 Sansome Street, Suite 400
San Francisco, California 94111

Re: AIM-II Project

Dear Bob:

This is in reply to your request for observations and comments on the meeting of July 30 and 31 and on the reports which had been prepared for that meeting. In addition, suggestions were also requested regarding the contents of the final report for Phase II, and for the scope of Phase III. In my opinion the project has been performed in a very credible manner. The presentations were very good as indicated by the interest and discussion from the participants.

As stated, the objective of Phase II was to "Demonstrate and Document Application of An Engineering Approach in Development of Platform AIM Programs". In other words, the project was to develop and illustrate a procedure, not to arrive at a specific answer for a particular platform based on a detailed study. For purposes of discussion, the project can be divided into two areas - Analysis or Technical, and Evaluation. The analysis portion was well done, quite possibly in more detail than required to illustrate the procedure. Also, more work was performed in this area than the participants paid for when the actual cost is compared to the project.

The technical area included two main work areas, Wave Prediction and Loading, and a Calculation of Ultimate Limit State. Most of the effort in the study appears to have been spent in this area. It was also the area of primary interest to most of the participants at the meeting. Unfortunately, this did not allow sufficient time for discussion of the evaluation area. Also, the participants at the meeting provided very little guidance to PMB covering the subject of evaluation. For this reason most of the review will discuss the subject of evaluation rather than analysis.

During the technical discussions one area which seemed to be of concern was the method used to model the deck for wave load. The equivalent single horizontal member, as adjusted, was certainly adequate for purposes of this study. However, for continuing studies it is suggested that several horizontal members (rungs of a ladder) be used. This would allow a more gradual increase in force as the wave height increases. The extra engineering effort would be minimal and probably less trouble than additional explanations. This is suggested only if the project is continued into Phase III. The technical work for Phase II is complete and entirely adequate. No additional work in the technical area is recommended.

While the technical work performed for this project was very good, it is my opinion that a major contribution from the AIM project is the evaluation procedure. Most of the participants in the study have the capability of analysis of wave loading and failure analysis. Although these analyses systems may not be as orderly as that developed for this project. It is expected however that few of the companies participating have developed a commercial evaluation procedure as presented. This portion of the study should be emphasized in the final report. It is recommended that some minor additions be considered as part of the preparation of the final report.

Although beyond the scope of this project some statement should be included regarding the net worth or the projected income expected for the platform or facility. As shown on the "Failure Cost" summary, a "Net Cost" of zero may be misleading. Even though it is obvious, some simplified estimate of net recoverable value would help complete the AIM evaluation presentation. The expected revenue must justify the cost or the facility should be abandoned, not repaired.

In addition, it is recommended that the cost of the consequences of the failure should be included. As an example, it is likely to be substantially more expensive to salvage a collapsed platform and to plug the abandoned wells which are bent, leaning and possibly completely broken off. In addition, there is the remote possibility that the storm chokes will not hold. The cost of killing a well which is out of control, possibly even a blowout and the resulting pollution and cleanup needs to be considered. Even though the possibility of the failure of a storm choke is very low, the effects are substantial. Information on these failures should be available through the API or other industry sources. However, any available data should be carefully evaluated since it may be out-of-date, not covering the improvements that have been made to down hole safety systems.

In addition, as suggested during the meeting, the removal of the platform and plugging the wells when the lease is terminated is a normal experience. Generally an allowance for this cost has been accrued. This should not be considered in the AIM evaluation. However, the added cost of salvage and well abandonment after a platform has collapsed should be considered. To illustrate the consequence of failure on the AIM decision-making process a revised "Failure Cost" summary has been prepared and is attached for both Platforms A and B. The effect on the AIM cost calculations are also included as marked in red. These are order of magnitude reports generally in the proper range. They are included for evaluation purposes only. In addition, an allowance has been included for new pipeline risers and for the tie-in and repairs to the existing pipelines.

These additions shown on the attachments are intended to more completely take into account the total cost of failure. If accurate rather than order of magnitude figures are used, the results may well change the favored alternate. Taking into account the total cost of failure makes the less risk approach more economical. Again, the figures which are presented are not intended as accurate estimates.

For the final report for Phase II it is recommended that the write-up in the June "AIM Progress Report to Participants" be up-dated and included. One subject area which should be given more detail is the reason for or necessity of using the ultimate limit state as the basis of reference. Since the platforms were designed for different use, their standards and design criteria depends on owner choices and the time the design was performed. The ultimate limit state provides the only constant basis for comparison. An explanation justifying this would certainly be beneficial.

In addition, some added discussion might be considered regarding the risk of human life. A detailed "how-to-do-it" would certainly be beyond the scope of Phase II. In the Gulf of Mexico due to the evacuation program the risk of life during storm is not normally a problem. For other areas where the design event can occur while the platform is manned, some discussion of how this should affect the evaluation should be considered. In the Appendix to the meeting report some hurricane damage statistics were listed. In case you wish to give a reference, this was published by the Marine Board as "Hurricane Loss" - <u>Safety and Offshore Oil - Background Papers 1981</u>.

To complete this review in a short time very little effort has been spent on suggestions for Phase III. The scope of work discussed during the meeting should be adequate. The evaluation of two additional actual platforms would certainly be beneficial. However, it is recommended that more effort be expended toward the evaluation phase rather than improving the analysis procedures. In Phase II the scope allowed very little time toward the regulatory aspects of evaluation. The commercial evaluation on the part of the owner was adequately covered. For Phase III it is recommended that substantial effort be devoted to assisting the regulator who is responsible for the evaluation process. It should be pointed out how the proposed repairs affect the "as-designed" condition of the structure. In many instances the "as- designed" has been the only tool the regulator had available. A comparison to this may be beneficial. In addition, further thoughts and discussion on how to blend the owners and

August 10, 1987

public cost in a decision-making process would be desirable. The AIM project is continuing to develop an evaluation process beneficial to the owner and the industry. It needs to be expanded to be of comparable benefit to the regulator. Otherwise, we may have a technical tool which cannot be accepted.

To summarize a lengthy project in a short letter is rather difficult. This is intended to be a brief summary. Please advise if you wish additional detail or discussion. The opportunity of performing this work is certainly appreciated.

Very truly yours,

Griff

Griff C. Lee

GCL:am
Encls.

cc B.Gerwick

PLATFORM A

FAILURE COST

		COST in $ Millions
A. Net Value of Facility		
Recoverable Production		
9 wells @ 500bpd @ $20.00 x 12 Years	394.0	
Less Total Production Cost		
Work over, Operations & Repairs	-296.0	
Net Recoverable		98.0
B. Less Lease Abandonmnet Cost		
Remove Platform (Existing Condition)	1.0	
Plug & Abandon 9 wells (From Platform)	2.3	
Total Abandonment Cost		3.3
NET VALUE OF FACILITY		94.7
C. Restoration Cost		
Salvage Platform (Collapsed)	4.0	
Plug & Abandon 9 Wells (Damaged)	10.0	
Less Normal Abandonment Cost	-3.3	
Total Additional Cost		10.7
D. Well Control and Polution Clean Up Cost		
Well Control (Blow out or Wild Well)	20.0	
Polution Clean Up	10.0	
Sub total	30.0	
Probability of Failure of Storm Choke- 3.0%		
Cost 9 Wells @ 3.0% x $30.0		8.1
E. Replacement Cost		
Platform & Equipment	4.4	
ReDrill Wells	22.5	
Pipeline Risers, Repairs & Tie-In	3.0	
Total Replacement Cost		29.9
TOTAL CLEAN UP AND REPLACEMENT COST		48.7

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PLATFORM A

AIM COST CALCULATIONS

$$E(C) = E(I) + E(F)$$

Conditions:

- 12-Year Remaining Life
- Platform Replacement
- C_D = 0.7

Alternative 1: Do Nothing

E(I):	.40 M		
E(F):	- Platform Capacity (Damaged Curve)	=	948 k
	- Return Period	=	42 Years
	- Cost = 3.3 + 26.9	=	~~30.2~~ 48.7 M
E(C) =	.40 + (1/42) x ~~30.2~~ 48.7 x 12		
E(C) =	.40 + ~~8.63~~	=	~~9.03~~ 14.3 M

Alternative 2: Repair

E(I):	1.7 M		
E(F):	- Platform Capacity (Repaired Curve)	=	1060 k
	- Return Period	=	45 Years
	- Cost	=	~~30.2~~ 48.7 M
E(C) =	1.7 + (1/45) x ~~30.2~~ 48.7 x 12		
E(C) =	1.7 + ~~8.05~~	=	~~9.75~~ 14.7 M

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PLATFORM A

AIM COST CALCULATIONS (Cont.)

E(C) = E(I) + E (F)

Alternative 3: Repair and Grout

E(I):	1.75M		
E(F):	- Platform Capacity (Repair and Grout Curve)	=	1155 k
	- Return Period	=	50 Years
	- Cost	=	48.7 ~~30.2~~ M
E(C) =	1.75 + (1/50) x 48.7 ~~30.2~~ x 12		
E(C) =	1.75+ ~~7.25~~	=	13.4 ~~9.00~~ M

Alternative 4: Repair and Raise Deck

E(I):	2.70 M		
E(F):	- Platform Capacity (Raise Deck Curve)	=	1440 k
	- Return Period	=	180 Years
	- Cost	=	48.7 ~~30.2~~ M
E(C) =	2.7 + (1/180) x 48.7 ~~30.2~~ x 12		
E(C) =	2.70 + ~~2.01~~	=	5.9 ~~4.71~~ M

PLATFORM B

FAILURE COST

		COST in $ Millions	
A.	Net Value of Facility		
	Recoverable Production		
	5 wells @ 500 bpd @ $20.00 x 5 Years	91.2	
	Less Total Production Cost		
	Work over, Operations & Repairs	-68.4	
	Net Recoverable		22.9
B.	Less Lease Abandonmnet Cost		
	Remove Platform (Existing Condition)	0.5	
	Plug & Abandon 5 wells (From Platform)	1.5	
	Total Abandonment Cost		2.0
	NET VALUE OF FACILITY		20.9
C.	Restoration Cost		
	Salvage Platform (Collapsed)	2.0	
	Plug & Abandon 5 Wells (Damaged)	6.0	
	Less Normal Abandonment Cost	-2.0	
	Total Additional Cost		6.0
D.	Well Control and Polution Clean Up Cost		
	Well Control (Blow out or Wild Well)	20.0	
	Polution Clean Up	10.0	
	Sub total	30.0	
	Probability of Failure of Storm Choke- 3.0%		
	Cost 5 Wells @ 3.0% x $30.0		4.5
E.	Replacement Cost		
	Platform & Equipment	4.7	
	ReDrill Wells	12.5	
	Pipeline Risers, Repairs & Tie-In	2.5	
	Total Replacement Cost		19.7
	TOTAL CLEAN UP AND REPLACEMENT COST		30.2

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PLATFORM B

AIM COST CALCULATIONS

$$E(C) = E(I) + E(F)$$

Conditions:

- 5-Year Remaining Life
- Platform Replacement
- $C_D = 0.7$
- Maximum Breaking Wave (46')
  Return Period = 275 Yr.

Alternative 1: Do Nothing

E(I):	0.15 M		
E(F):	- Platform Capacity (Damaged Curve)		X = 1135 k Y = 760 k N = 1000+ k
	- Return Period		X = 115 Yr Y = 12 Yr N = 10000+ Yr
	- Cost	=	~~19.2~~ 30.2 M
E(C) =	0.15 + (1/12 - 1/275) x ~~19.2~~ 30.2 x 5		
E(C) =	0.15 + ~~7.67~~	=	~~$7.80~~ 12.2 M

Alternative 2: Remove Boat Landings and Marine Growth

E(I):	0.35 M		
E(F):	- Platform Capacity	=	760 (Y)
	- Return Period	=	20 Yr (Y)
	- Cost	=	~~19.2~~ 30.2 M
E(C) =	0.35 + (1/20 - 1/275) x ~~19.2~~ 30.2 x 5		
E(C) =	0.35 ~~+ 4.45~~	=	~~$4.80~~ 7.4 M

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PLATFORM B

AIM COST CALCULATIONS (Cont.)

$$E(C) = E(I) + E(F)$$

Alternative 3: Repair Elements			
E(I):	0.45M		
E(F):	- Platform Capacity	=	760 k (Y)
	- Return Period	=	12 Yr (Y)
	- Cost	=	~~19.2~~ 30.2 M
E(C) =	0.45 + (1/12 - 1/275) x ~~19.2~~ 30.2 x 5		
E(C) =	0.45 + ~~7.67~~	=	~~8.12~~ 12.5 M

Alternative 4: Repair and Raise Deck			
E(I):	1.45 M		
E(F):	- Platform Capacity	=	760 k (Y)
	- Return Period	=	12 Yr (Y)
	- Cost	=	~~19.2~~ 30.2 M
E(C) =	1.45 + (1/12 - 1/275) x ~~19.2~~ 30.2 x 5		
E(C) =	1.45 + ~~7.67~~	=	~~9.12 M~~ 13.5

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August 12, 1987

PMB Systems Engineering, Inc.
500 Sansome Street
San Francisco, CA. 94111

Attention: Mr. Robert Bea

Subject: A.I.M.

Dear Bob:

I was very pleased to be able to participate in your A.I.M. II meeting last week. You and your colleagues have carried out a tremendous effort on an extremely important but difficult task.

As I understand it, you're trying to find a practicable methodology that will enable you to assess the safety of an existing platform for a finite, but relatively limited period of years. Input data will include any damage, or deterioration as revealed by inspection and the latest approaches to storm waves and currents, drag, and soil-structure interaction.

As you suggested, it may be possible to develop a simplified screening test which would help to sort out those structures needing more detailed investigation.

One such test would of course be the question of whether or not a storm wave would hit the deck. Usually structures stand pretty well up to that time but once the deck is impacted, then forces and overturning moments rise dramatically. What wave to use? Many years ago you developed the thesis then for a 25 year life, you should use the 100 year return wave. ABS uses a figure, as I recall of 5 times the design life. In the examination of an existing structure for which the owner/operator wishes to extend the life for a known period, eg. 8 years, why not use the 5 times 8 or 40 year return storm?

You and your associates carried out in-depth computer evaluations of the two test structures in both the elastic and plastic ranges. As Griff Lee has pointed out, you probably went further into these analyses than was required by your project scope. The question is where to stop? For example, in one case where horizontal bracing was missing (I think this was B) you analyzed the structure for waves from both orthogonal directions but didn't include an oblique wave, which would have of course produced torsion.

More important, as pointed out in the meeting, while such analyses are certainly state-of-art within the operator's company or his consultant, can they afford the time and costs to so evaluate all their existing platforms?

In the case of both your examples, you got to a limited zone at the break point which was critical. Is there any way of identifying this at an early stage and confining the analysis to that zone only?

Since in the plastic range, near ultimate, the best calculations are only approximations, is there someway of simplifying the computational effort at this critical zone?

Well, I'm sure you've given considerable thought to these aspects already.

Griff Lee and I have discussed the A.I.M. Project meeting by telephone. I understand that it's appropriate for us to exchange ideas and hopefully synergize something helpful.

Both of us feel that there is a need now to concentrate effort on the "evaluation" phase. So far this appears to have been dealt with only partially.

I believe that you need to include in the evaluation the present value of the resource. If the reservoir production doesn't justify the repair or renovation, then it's best to just remove the platform now.

I suggest that you use "present value" for all future expenses and benefits. Even for a five year remaining life, at 10%, the present value is only 60% of the total. I know you've suggested that inflation offsets interest but that's not really true. What economists would ask you to use, I believe, is management's required Internal Rate of Return. Anyway, since you're developing a procedure, why not include PV, it's a very simple hand calculation.

The costs of failure also need to be amplified. Pat Dunn pointed out that storm chokes are only 95% (or is it 98%?) reliable, that with a platform with 20 wells, there's a probability that one of them won't work and thus you need to include the cost of pollution, which of course is enormous. Presumably here also one would assign a present value to this future cost.

Griff will be writing you separately concerning the costs of replacement, which he feels may need to be amplified.

Have we considered, as an alternate to replacement, the external strengthening by means of additional structure and piles? That way we wouldn't have to drill new wells, new risers, new pipeline connections, etc.

There's a very large intangible cost, not only to the Operator of a particular platform, but to the industry, in the event of a failure of that platform, especially if accompanied by pollution. That is the probable imposition of upgraded and accelerated requirements for inspection, evaluation and repair of all other existing platforms, at least in that area or class.

Somewhere in the next phase or phases, more attention has to be given to the concerns of the Regulator. Until now, he's satisfied when the Operator tells him the platform is as safe as when initially installed. Yet as you have pointed out, the drag factor may have been inadequate, the design wave too low, and the soils inadequately evaluated.

Further the Regulator's valuation of failure may be far different than the Operator's. Pollution may present grave political problems. Loss of life may have implications insofar as procedures, hurricane weather reporting, etc., beyond that associated with the one platform.

You discussed historical risk. The industry standard is a P(F) of 10^{-4} per year. When we use a 100 year return wave, and then apply a load factor of 1.3 or 1.4, in reality we're trying to get to a P(F) of 10^{-4}. The accident case, as defined by DNV is 10^{-4}. Is there someway in which we could quantify the probability of failure of an existing platform and thus satisfy the Regulator?

You brought up "Third Party Verification" as one possible approach, and asked Griff Lee and myself to look at this. The original Marine Board Report dealt with new platforms only and only those in deep water or new environments. It's obviously impractical to use "third party verification" on all existing platforms.

What might be considered is a "Third Party Review" or "Third Party Evaluation" which would follow simplified procedures to screen those warranting closer scrutiny.

Third Party Verification could still of course be applied to damaged major structures (deep water and new or especially severe environments).

I have a few more technical comments and questions:

1. In your evaluation of the ULS performance, I believe you're not using any material factor (and in fact are using average, not minimum values). Are you using any load factor? You're now using historical and hindcast waves, so the uncertainty there is reduced. On the other hand, the highest wave in a storm has a 63% probability, as I recall, of being higher than "the most probable highest wave". Without a load factor, are we now adequately conservative?

2. Have you considered wave slam on the underside of the deck, whenever the wave crest impacts the deck? The uplift forces are very high.

3. When an existing platform has several damaged braces, is it necessary to repair them all? There's undoubtedly a case where partial repair would be adequate for a finite life.

4. As pointed out during the discussion of platform B, the trough of a hurricane wave from the south may impact more force from the north than the crest of a "norther".

As a suggestion, I think it might be useful to discuss some of these matters sometime convenient, especially if we can arrange for Griff to also be here.

Sincerely,

Ben

Ben C. Gerwick, Jr.

cc: Mr. Griff Lee

/sk

APPENDIX F

COPY OF PAPER BY R. G. BEA AND C. E. SMITH

THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
601 Pavonia Avenue, Suite 400, Jersey City, New Jersey 07306
Paper presented at the Marine Structural Reliability Symposium, Sheraton National Hotel, Arlington, Virginia, October 5-6, 1987

AIM (Assessment, Inspection, Maintenance) and Reliability of Offshore Platforms

R.G. Bea, PMB Systems Engineering, Inc., San Francisco, California
C.E. Smith, Minerals Management Service, Reston, Virginia

ABSTRACT

Concerns for requalification of existing fixed offshore platforms have served to focus a need for development of a practical engineering approach to the AIM (Assessment, Inspection, Maintenance) aspects of these structures. The principal concerns for requalification are focused on older platforms that are now in service, and that are providing a resource critical to U.S. energy requirements.

This paper defines one approach to the AIM process for fixed offshore platforms. Probabilistic methods are applied to several key parts of this approach. These include assessments of operating and environmental forces, the as-is and repaired capacities of the platform, and analyses of alternative remedial maintenance programs.

INTRODUCTION

Today, there are some 6,000 fixed offshore platforms sited on the world's Continental Shelves. Many of these structures have been in place for over 30 years.

Renewed drilling activity to further develop known reserves, and supplemental recovery operations indicate the need to requalify these structures for extended lives. In addition, there are extremely strong pressures to minimize costs, particularly in the light of depressed oil prices.

These developments have resulted in the vital concern with requalification of existing platforms. Fixed platforms have had an enviable safety record, and the objective is to maintain this record as platforms enter their twilight years.

AIM REQUALIFICATIONS

The AIM engineering approach to requalification of platforms involves three primary interrelated elements in what will be termed the platform AIM triangle (Fig. 1):

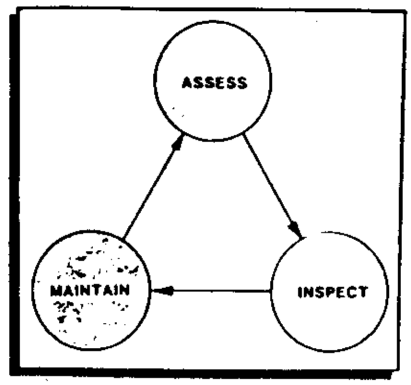


Fig. 1 Platform A I M Triangle

1. Assess - those engineering appraisals intended to evaluate present and future platform serviceability, determine the desirable characteristics of present and future serviceability, and examine alternative platform maintenance programs with the objective of identifying practical maintenance programs that will develop acceptable platform serviceability characteristics while preserving essential safety, economic, and environmental objectives.

2. Inspect - those engineering and operations programs directed toward detection and documentation of significant defects or damage in a platform that can lead to potentially significant reductions in platform capacities and serviceability characteristics.

3. Maintain - those engineering and operations programs developed and implemented to preserve or enable a platform to develop acceptable capacities and serviceability characteristics.

The AIM triangle indicates a continuing process of platform requalifications intended to keep platforms in service by using preventative and remedial engineering/operations techniques. The AIM process is intended to be one of progressive and continued reduction of risks to tolerable and acceptable levels.

The AIM approach is positive. Inspection, definition of defects and damage, and repairs or improvements are given high priority in platform operations, with an objective of establishing and maintaining the integrity of a given structure at the least possible cost. Practicality implicates an incremental investment in identifying and remedying platform defects in the order of the hazards they might represent. This is a prioritized, learn-your-way-through approach.

The focus of the AIM approach (Fig. 2) is on identification of high hazard potential structures that may possess significant defects or damage, and how to define cost effective, professionally acceptable, and practical solutions for these structures. The benefits of AIM engineering and operations activities must be justified by the benefits that are achieved and the resources that can be invested to keep a vital resource flowing to the market place.

The basis of the AIM approach is that the problem of a major platform with potentially significant defects is one that should be approached without rigid conformance to "conventional practice," maintaining a high level of technical and operational excellence, and defining creative and practical ways to lessen risks within the unavoidable constraints of currently available knowledge, manpower, money and time. This is a structure and problem-specific approach. It is not an engineering code or rigid guideline approach.

Unfortunately, at this time, there are no established engineering codes or guidelines for platform AIM. In this vacuum, many engineers would adopt current platform design guidelines and practices as a basis for evaluation of existing platforms.

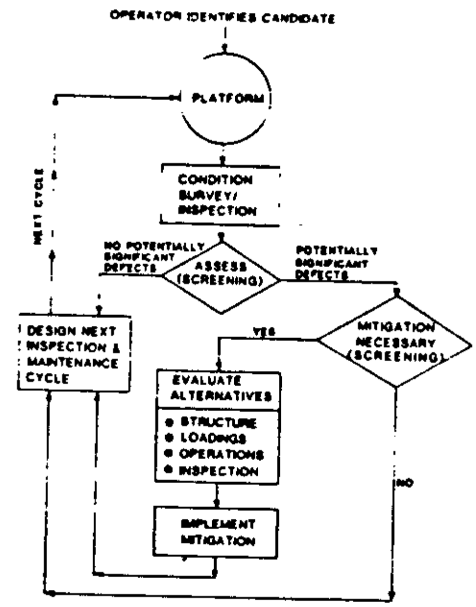


Fig. 2 A I M Approach

This can be a dramatic mistake for several reasons. Codes are general guides for practice. They cannot recognize many site, platform, and operation specific factors critical to platform requalifications. Codes are oriented to elements in a platform, and a general framework of common engineering practice. Codes are intended to result in a structure that is serviceable, safe, and economic.

Platform requalifications have a series of objectives that differ substantially from those of codes and guidelines intended for design of a structure. These objectives are those of realistically evaluating an existing platform which is frequently defective, and attempting to answer the question, "Will this structure, in its present condition, perform acceptably during its remaining life?" Alternatively, this question can be posed, "What can or should be done to allow this platform to perform acceptably during its next AIM cycle?" These objectives suggest a different set of engineering philosophies and approaches.

INITIATION

The AIM approach (Fig. 2) is initiated with the platform operator identifying a candidate platform. There are two principal considerations: 1) which platforms should be selected, and 2) how many platforms should be selected.

The first consideration is basically one of identifying the priorities of the AIM process. The second consideration is one of determining the allocation of resources for the AIM process.

There are a wide variety of quantitative and qualitative ranking procedures which can be used in the platform selection process. One practical approach consists of two qualitative priority evaluation attributes: 1) consequence potential, and 2) defect potential. The consequence potential is the likelihood, given an extreme loading event, that there could be extensive damage to property, lives, resources, and the environment. The defect potential is the likelihood of deficiencies in design, construction, and/or operation of the platform. The essence of the defects is as they might affect the capacity of the platform to resist extreme events (Fig. 3).

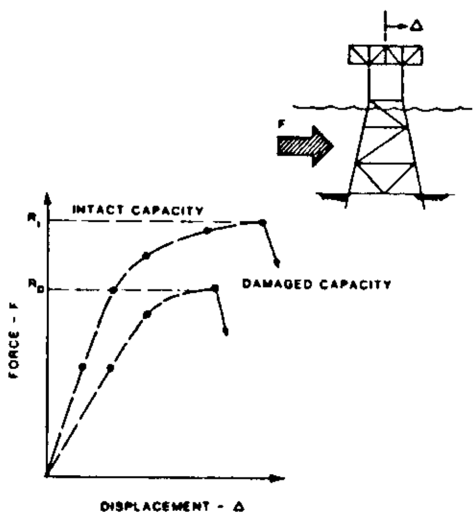


Fig. 3 Intact and Damaged Platform Capacities

Both of these potentials can be evaluated on a relative ranking scale, e.g., H = High, M = Moderate, L = Low. Knowledge of the structure, qualified judgment, and most importantly, the history of performance of the structure become the bases for the evaluation. The two evaluations are combined (Fig. 4) to result in nine different possible combinations of consequence and defect potentials. The first priorities for introducing a particular platform to the AIM process are given to those structures which possess both high consequence and defect potentials.

	DEFECT POTENTIAL		
CONSEQUENCE POTENTIAL	LOW	MODERATE	HIGH
LOW	L,L	M,L	L,H
MODERATE	L,M	M,M	H,M
HIGH	L,H	M,H	H,H

FIRST PRIORITY

SECOND PRIORITY

THIRD PRIORITY

Fig. 4 Platform Inspection Priorities

Now, given large number of platforms, the question becomes one of how many structures should be introduced to the AIM process? This is fundamentally a question of how much resource a particular operator feels is appropriate to invest in AIM programs, either for a specific platform or a fleet of platforms associated with some particular development.

At this time, there are no general or easy answers to this question. Quantitative cost-benefit analyses could be made based on the overall economics of a particular platform or development to assure that a reasonable investment of resources will be made to maintain the platform's abilities to perform acceptably during project operations [1-3].

CONDITION SURVEY

In this AIM step, a data bank is initiated or continued on a particular structure, including all available pertinent information on the design, construction, and operational history of this structure. Of major importance are identifying and recording exceptional events or developments. The greater the knowledge about a particular structure, then the more realistic is the evaluation, and the more effective the AIM program results. It is impossible to realistically evaluate a platform's performance or safety without definite information on the structure. The primary components that should be incorporated into a platform data bank are summarized in Table I.

An AIM program can only be effective if there is an adequate store of information on the platform or fleet of platforms. This store of information, or data bank, should contain information on the design, construction, operation, maintenance, and as-is condition of the platform. This data bank becomes vital in directing the course of inspection surveys -- determining which elements to inspect, what to look for, the methods to inspect, and the timing or frequency of inspections [4-12].

SCREENING

The next two AIM steps are concerned with assessing or screening the candidate platform's need for defect mitigation. Examples of platform defects are given in Table II. If there appears to be no potentially significant defects in the structure, the procedure is concerned with the engineering of the next inspection and maintenance cycle. If there appear to be significant defects, the next step is to determine if mitigation of these defects is necessary.

Mitigation of defects refers to a prioritization of remedying those defects, and identification of practical alternative remedial actions. The evaluation necessarily depends on the hazard potential of a given platform; given that the platform would not perform adequately during the next AIM cycle, and on the potential for such performance. If no mitigation appears to be warranted, the procedure again branches to the design of the next inspection and maintenance cycle for the platform.

EVALUATION OF MITIGATION ALTERNATIVES

If mitigation appears to be warranted, the AIM process branches to the detailed evaluation of the alternatives for mitigation (Table III). The alternatives include:

a. The structure itself - repairs to damaged, in-place, load-carrying members.

b. Loadings - removal of deck equipment, removal of marine fouling, removal of unused or unneeded elements (e.g. boat landings, risers, etc.).

c. Operations - improvement of corrosion protection, installation of additional well and production safety equipment, installation of additional personnel safety equipment, demanning in advance of storms.

d. Information - on-site inspections and measurements to improve detail of data on present condition of the structure, development of detailed information on past loading events.

IMPLEMENTATION AND DESIGN OF NEXT AIM CYCLE

Once the mitigation alternative has been defined, the next step is to engineer that alternative and implement it in the platform operations.

1. Design - Site data, criteria, guidelines, procedures, drawings, etc. pertaining to the initial engineering phase of the structure.

2. Fabrication - Specifications, materials, equipment, quality assurance procedures and reports, etc. pertaining to the onshore construction phase of the structure.

3. Transportation - Specifications, equipment, quality assurance procedures and reports, etc., pertaining to the load-out and transport of the structure to the offshore installation site.

4. Installation - Specifications, equipment, materials, quality assurance procedures and reports, etc., pertaining to the preparation for placement and replacement of the structure at the location.

5. Operations - Information pertaining to plaform loading and capacity characteristics and modifications that are developed during the drilling phase and during the production phase of operations of the structure.

6. Maintenance - Specifications, equipment, materials, procedures used to preserve or modify the capacity of or loadings on the platform.

Table I Platform Data Bank Components

1. Design

   a. Storm wave and current forces underestimated

   b. Earthquake forces underestimated

   c. Tubular joint design results in low capacity and short fatigue lives

   d. Conductor and riser wear on supports

   e. Insufficient corrosion protection

   f. Unanticipated scour

   g. Gravity load underestimated

2. Construction

   a. Misalignments of legs, braces, and joints

   b. Undercut welds

   c. Insufficient penetration welds

   d. Tank welds

   e. Lamellar tearing

   f. Insufficient pile penetration (lowering axial capacity, lowering lateral capacity)

   g. Load-out, transportation, and launch damage to primary structural elements

3. Operation

   a. Corrosion protection not maintained (above and below water)

   b. Boat bumpers and landings not maintained (resulting in damage to primary structural elements)

   c. Trash dumping (cables, pipe) resulting in damage to legs and braces

   d. Field modifications to structure (cutting holes in members, adding risers and riser supports, adding deck sections and deck cantilevers)

   e. Addition of well conductors and production risers above design

   f. Addition of deck equipment and loadings abode design

   g. Poorly engineered and implemented repairs to primary structural elements

4. Accidental

   a. Boat and barge collisions, resulting in damage to primary structural elements.

   b. Dropped objects resulting in damage to primary structural elements.

   c. Workover operations fires and explosions resulting in damage to primary structural elements.

   d. Production equipment fires and explosions resulting in damage to primary structural elements.

   e. Drilling fires and explosions resulting in damage to primary structural elements.

Table II Examples of Platform Defects

REDUCING PLATFORM DEMANDS - MINIMIZE LOADS AND LOAD EFFECTS

- Reduce deck loads - dead loads from equipment and facilities, live loads from storage
- Reduce wave and current forces - removal and prevention of marine fouling; removal of non-essential components and appurtenances
- Reduce wave and current forces - re-evaluation of wave and current conditions based on site (bathymetric), platform and operations (exposure period) specific conditions and BAST*

INCREASING PLATFORM CAPACITIES - MAXIMIZE STRENGTH OF ELEMENTS

- Increase strength of joints by grouting, welding, profiling, replacement
- Increase strength of primary and secondary members by doubler wraps, replacement, grout fill, secondary bracing, soil strengthening (foundation members)
- Add members - braces, piles, beams
- Re-evaluate Serviceability and Ultimate Limit States resistances and capacities based on platform, site, and operations specific conditions and BAST

REDUCING OPERATIONS EXPOSURES

- Reduce operations carried out onboard or adjacent to the platform
- Reduce deck equipment
- Reduce storage
- Reduce wells and risers
- Increase pollution control, clean-up equipment and measures
- Increase well and production protection equipment and measures
- Reduce manning requirements
- De-manning in advance of anticipated/forecast hazardous events
- Reduce boat/barge transfer operations with equipment tied to platforms or in hazardous conditions
- Reduce frequency of well work-over operations
- Additional effective life-saving equipment and injury treatment facilities and procedures
- Additional training of operations personnel in conduct of safe operations and maintenance of facilities
- Reduce unengineered field alterations to the structure

INCREASING MAINTENANCE EFFECTIVENESS

- Increase corrosion protection - above and below water
- Increase scour protection
- Increase frequency and extent of inspections and conditions surveys
- Increase effectiveness of operations to maintenance engineering reporting systems

*Best Available and Safest Technology

Table III Examples of Platform Hazard Mitigation Alternatives

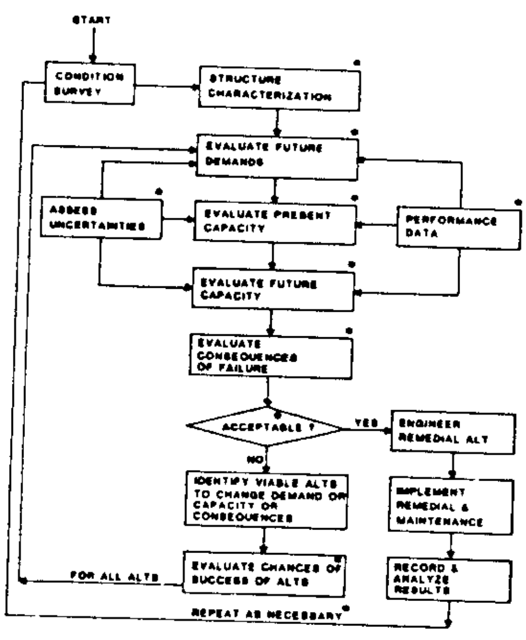
The results of this implementation are incorporated into the platform condition survey/inspection data bank.

The final step concluding an AIM cycle for a platform is that of designing and implementing the next inspection and maintenance cycle. The length of the cycle will depend upon the projected performance characteristics of the platform, and the need for and benefits of improving knowledge and data on the platform condition and performance.

RISK ANALYSIS

The risk analysis that will be discussed is basic, appropriate for a practical engineering state-of-practice to develop AIM programs. The reader is referred to references [3-21] for background on more comprehensive risk analyses.

The approach (Fig. 5) has been cast in a demand versus capacity format. "Demand" refers to future loadings that may be imposed on the structure. "Capacity" refers to future resistances (or ability to carry loadings) of the structure. The capacities that will be of primary concern are those that connote primary consequences of the loss of serviceability of the platform. The probabilities of the demands exceeding the capacities of the structure will be termed the probabilities of failure.



* PRIMARY POINTS OF POTENTIAL APPLICATION OF PROBABILISTIC METHODS

Fig. 5 Risk Analysis Approach

Uncertainties and probabilistics are important ways of describing the structure. They are based on the knowledge provided by the condition survey(s), the future demands (e.g. knowledge of environmental forces), and the future capacities (e.g. knowledge of the load-carrying capacity of the platform). The basics of the approach are deterministics; assessments of uncertainties are added to make the picture more complete. Experience and performance data on either the demands or the capacities play a vital role in assuring reasonable characterizations of these items.

Risk (P_f) will be defined as the probability (P) that the platform's lateral capacity (R_c) is equal to or less than the maximum lateral loading (S_m) imposed on the platform during the exposure period (L):

$$P_{f_L} = P\,(R_c \leq S_m) \qquad (1)$$

The platform's capacity will be taken as the Ultimate Limit State (ULS) resistance or the maximum lateral force that can be imposed on the platform before collapse (unable to support vertical loadings).

Note that the platform's capacity will be dependent upon the as-is condition of the platform's members and upon any changes that might take place in this condition. Such changes might take place as the result of strengthening or rehabilitation measures, or as the result of fatigue, corrosion, or operations damage. Further, note that the platform's lateral capacity will be conditional upon its vertical loadings (as-is, altered in future).

The platform's demands will be expressed as the maximum lateral loadings or forces that could be developed by storms (combination of wind, wave, and current forces) or other similar events that could occur during the platform's exposure period.

The platform's exposure period risk (P_{f_L}) will be related to its annual risk (P_{f_a}) as follows [22]:

$$P_{f_L} = 1 - (1 - P_{f_a})^L \qquad (2)$$

or approximately,

$$P_{f_L} = (P_{f_a}) \cdot L \qquad (3)$$

The environmental lateral loadings will be taken as the dominant source of variability and uncertainty. The uncertainties and variabilities associated with the platform's lateral capacity can be evaluated by determining the changes in risk that develop as a result of changes in the evaluated capacity.

The annual platform risk (annual probability that demand will exceed capacity) is determined as a function of the return period (RP_C) of the storm that develops lateral loads equal to the platform's capacity or ULS resistance:

$$P_{f_a} = 1/RP_C \qquad (4)$$

DEMANDS

Characterization of the demands that can be imposed on a platform starts with evaluation of the likelihood of experiencing various intensities of events. These events could be environmental (e.g. developed by hurricanes or earthquakes), or they could be operational (e.g. due to drilling and production activities).

For example, measurements and analyses of hurricanes affecting the northwest Gulf of Mexico [23,24] could develop information on the Average Return Periods (ARP), $\bar{T}$, associated with different possible maximum wave heights occurring at a given platform location (Fig. 6). The ARP's express the average time between occurrences of wave heights that equal or exceed a given maximum wave height (H_m).

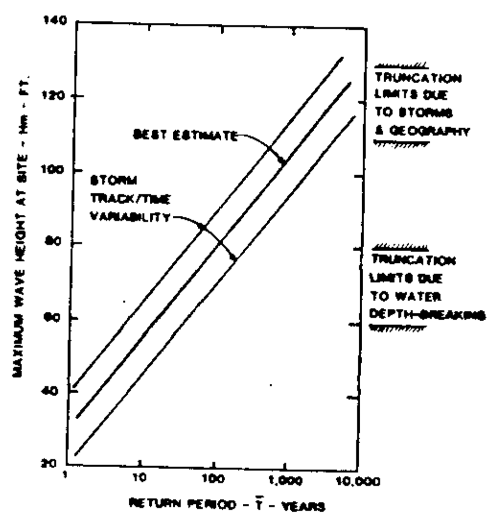


Fig. 6 Wave Heights Vs. Return Period

A similar illustration could be developed for any source of demands. For example, for earthquakes, meaningful measures of the intensity of ground motions (acceleration, velocity, displacement) would replace the wave heights [25].

The key element is to choose parameters that adequately describe the force effects developed by the source of the demand.

Generally, there are two primary sources of variability with regard to environmental demands: intensity and proximity. For example, the heavy line in Fig. 6 represents a typical site in a geographical region. The wave heights are primarily a function of variable storm intensities. The scatter band indicated around the heavy line indicates the uncertainties contributed by proximity, or storm tracks in the case of hurricanes. Both sources of uncertainty should be considered to determine the resultant uncertainty of the occurrence of maximum wave heights at a given platform location.

It is important to recognize site-specific effects, and see that these are properly reflected in the evaluation of uncertainties. For example, shoaling effects at a given location could indicate wave heights that are substantially different from a typical or "average" site condition [26]. Also note that the site can exert important limiting or truncating effects on what could otherwise be a continuous or unlimited distribution of potential wave heights (Fig. 6). Water depth and breaking wave processes place a physical limit on the maxium wave heights that can be developed in shallow water locations. Similar types of site-specific and source-specific factors can place important limitations on the maximum magnitudes of many types of environmental demands.

The next step of the platform demand characterization concerns the prediction of loadings or forces, given the measure of the demand intensities. In the case of hurricanes, given the maximum wave heights, this step determines the loadings on the platform of concern (Fig. 7). This involves computing hydrodynamic forces for the range of wave heights of interest. Other forces of potential concern are those generated by the water currents and winds that occur at the time of the maximum waves. Note the conditionality of the combination of winds, waves, and currents. It is not the maximum wind, wave and current. It is the combination that produces the maximum forces or force effects on the platform. The conditionality not only applies to the magnitudes of the other sources of loading, but also on their directions.

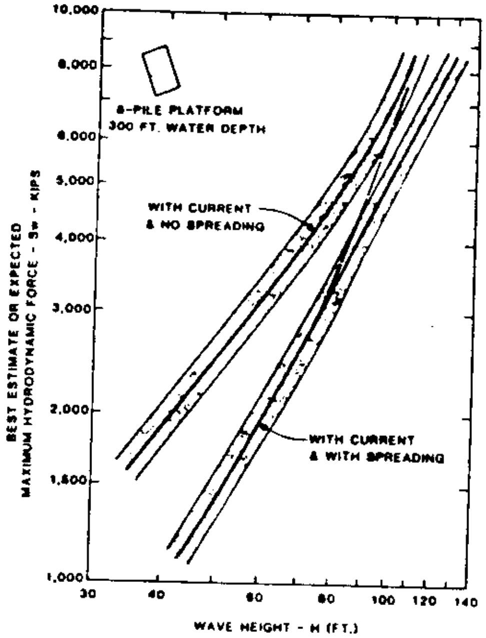
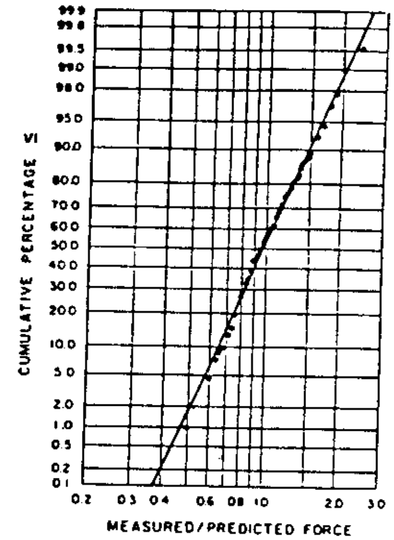


Fig. 7 Influence of Current and Wave Spreading on Hydrodynamic Forces



(PREDICTED FORCE = API GUIDELINE WAVE FORCE, C_D= 0.6, C_m=1.5, NO CURRENT)

Fig. 8 Correlations Between Measured and Predicted Wave Forces

The problem of force prediction is complex, and thus it may be necessary to characterize the forces in a parametric manner, investigating the potential influences of various elements involved in the prediction of forces. For example, one might wait to investigate the effects of including and excluding the hydrodynamic forces associated with directional wave spreading (understanding that the greatest amounts of directional spreading are associated with the maximum wave heights near the storm center).

In this regard, results from recent wave force measurement programs can provide important sources of information to calibrate or verify conventional hydrodynamic force models (Fig. 8). Results from a full-scale instrumented platform in a water depth of 175 feet subjected to maximum wave heights up to 40 feet, and associated surface currents in the range of 1.9 to 3.8 feet per second, indicate that a conventional hydrodynamic force model tends to substantially over-predict the true forces [27,28]. The overprediction exceeds 100 percent when plausible combinations of currents and marine fouling effects are included: the mean ratio of measured to computed force ranges between 0.44 and 0.8. The coefficient of variation (measure of scatter) on the predicted versus measured forces falls in the range of 20 to in excess of 45 percent.

Since the hydrodynamic force computations involve major modeling assumptions concerning computations of wave kinematics, wave propagation through the structure, forces and force coefficients shielding, roughness, etc., the questions regarding the true or best estimate forces must be carefully weighed in contrast to conventional (and intentionally conservative) formulations used in design practice [29].

Note that in this step, it is important to use force prediction methods that result in unbiased predictions of the forces. Bias is defined as the ratio of the true or expected value of the parameter to its nominal or computed value. In this stage of the demand characterization, we want the ratio of true to predicted force to be near unity.

Also note that one could choose to focus the analyses on global load effects (such as total lateral base shear or total overturning moment at the seafloor) or local member load effects (such as the maximum forces in a brace, joint, or pile). In the remainder of the discussion that follows, the focus will be on global demands exerted on the platform. This is not meant to exclude the possibility of conducting similar analyses of elements or structural subsystems within the platform, for these may be of vital interest as well.

The final step in the demand characterization is the one of computing the maximum forces or force effects on the platform, based on the results of the first two steps [30]. The result (Fig. 9) is the characterization of the likelihood (expressed as the ARP) of various possible magnitudes of maximum demands (expressed as the total lateral force on the platform).

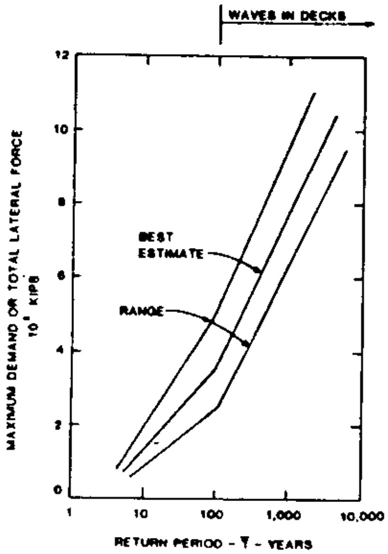


Fig. 9 Platform Demands

CAPACITIES

Platform capacities can be described in Serviceability Limit State and Ultimate Limit State behaviors where:

a. Serviceability Limit State (SLS) - demands or loading-deformation conditions under which the function of the structure may be impaired; damage results, but collapse is not imminent, nor is the platform rendered unserviceable.

b. Ultimate Limit State (ULS) - demands or loading-deformation conditions under which the structure is no longer serviceable, or is unable to fulfill its intended functions.

Capacities generally have been characterized in a resistance-deformation format for the entire structure system (Fig. 10). Generally the capacities are described by load or force resistances, although displacements or deformations may even be more descriptive. For example, if the structure is loaded so that a significant permanent tilt is developed in the structure, its load resistance may be relatively unaffected, but the structure is rendered unserviceable.

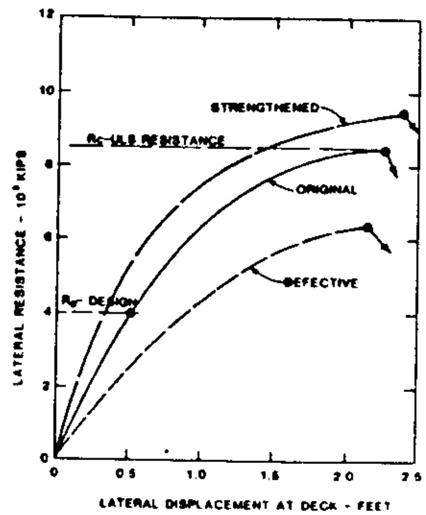


Fig. 10 Capacities of Original, Defective and Strengthened Platform

Capacity of the platform must be characterized in terms that are important to the serviceability properties of the system. In this paper, capacity of the system will be defined in terms of the static, lateral load resistance at which the system is unable to support its gravity or vertical loadings (R_C, Fig. 10). This state will be termed collapse or failure.

Due to the transient nature of most environmental loadings, the structure may or may not be in a true state of failure at this point. Limitations in practical analytical methods to define platform capacity make the definition only an index or imperfect reflector of the behavior of a structure at ULS.

There is a variety of engineering analytical methods to define the platform capacities. Conventional linear elastic analytical methods, such as those used in most design practice, have deficiencies in their abilities to characterize platform ULS capacities. This is due to nonlinear, behavior of platform elements at high loading levels.

Nonlinear, inelastic analytical methods, such as those used in design practice for severe earthquake prone regions, are the best presently available approach for characterizing behavior of the platform at the ULS. However, this approach suffers from complexity and from the general unfamiliarity of most engineers with the technology of nonlinear, inelastic analyses. Even in their simplest form, nonlinear static pushover analyses represent a significant engineering effort although the analytical tools are available [31-35].

To perform time-domain, nonlinear, inelastic structural analyses that properly track the ULS behavior of the structure requires an even more significant effort. Such analyses have been performed for relatively few structures [36-38].

In between these two extremes of analytical approaches lie equivalent linear methods that attempt to mimic the essential elements of nonlinear behavior, yet retain the basic computational tools of linear elastic analyses [16,39-41]. Such approaches require extensive studies of nonlinear behavior in typical platform systems or sub-systems. The results are used to guide the equivalent linear approximations to the true or best estimate nonlinear behavior. The guidance becomes dependent on the particular platform systems or sub-systems studied, and thus lacks generality. However, given sufficient development, this approach represents a practical alternative to either conventional linear elastic methods or nonlinear inelastic methods.

Generally, major AIM concerns with evaluating platform capacity will address the platform in its original (designed), as-is defective (damaged), and possibly strengthened (rehabilitated) conditions (Fig. 10). These capacities become the basis for judging the integrity of the structure and evaluating alternatives for its rehabilitation.

Repair Effects

The effectiveness of alternative repair or rehabilitation measures on the platform capacity should be carefully considered from several standpoints. Experience has shown that repairs to tubular joints and members and foundation elements are major engineering challenges [4,44-47]. These repairs are limited by the practicalities of what can reasonably be accomplished offshore (and often underwater). They call for innovative and effective engineering strategies for repairs that balance strength, stiffness, and ductililty of the single component and the structure system.

Experience has also shown that there is a potential liability that occurs from a poorly designed or poorly executed repair. In more than one case, attempts to repair a component have done more damage than leaving it alone. In some cases, damage has been done to other parts of the platform in the course of attempting the repairs. The potential effects of plausible downside outcomes of platform repairs should be investigated and considered before a repair scheme is selected.

Careful engineering analyses of alternative repair schemes can define effective and practical solutions to difficult repair problems. Evaluations of the results of repairs should include an evaluation of the expected, up-side and down-side effects of the repairs on the platform capacity (Fig. 11).

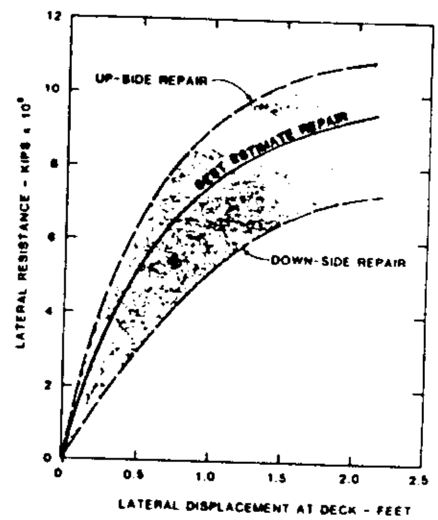


Fig. 11 Effect of Repairs on Platform Capacity

Provision of a rational basis for selecting a remedial alternative (mitigation measure) in the case of a damaged or defective platform is critically important. When condition surveys indicate that some platform element is damaged, the first tendency is to conclude that it must be repaired. In some cases, this is a valid conclusion. However, in many instances repair is unnecessary for the following reasons:

a. Platforms are generally designed to be highly redundant. This redundancy is an investment in producing a highly damage tolerant structure. Even though it is damaged, the structure's capacity may not be seriously affected. Alternative load paths may provide the necessary backup.

b. Platforms are generally designed and constructed with many explicit and implicit sources of conservatisms. Site- and platform-specific conditions may be such that even if there has been some reduction in the capacity of the structure as the result of damage or defects, the structure is still acceptable and highly serviceable.

c. There may be more effective mitigation measures to assure safe operation of the structure. Load (or demand) controls and operation controls can frequently be more effective and less costly in providing a structure that has acceptable serviceability characteristics.

d. There are many elements in a platform that are not important to in-place capacity or performance. Generally these elements are associated with construction (fabrication, transportation, installation) of the structure. Damage to these "secondary" elements does not necessarily imply that there has been an important decrease in the in-place capacity of the platform. Note that these secondary elements or systems can provide important back-up sources of strength to the primary in-place load-carrying members.

Fatigue Considerations

One important AIM concern is potential fatigue damage to platform elements. Fatigue damage, or the reduction in capacity and stiffness as the result of repeated loadings, is present to some extent in all of the platform superstructure and foundation elements. Current fatigue design approaches for those elements are intended to minimize the potential for fatigue damage during the life of the structure [48-50].

A primary concern is with elements that have been damaged, or poorly fabricated, or perhaps underdesigned for fatigue. These problems are usually identified by inspections that show the presence of cracks in the joints and members of the structure, or perhaps by indications that the foundation elements are "softening" (e.g. scour pits around the piles).

For tubular joints and members, a conventional S-N (stress-number of cycles to failure) - Miners Rule (damage accumulation rule for combining different stress-cycle history effects) can do little to assist in characterizing the remaining capacity of a damaged tubular member or joint [51-53]. Conventional foundation analyses are also rarely appropriate [54].

Alternative fatigue analysis approaches have been and are being developed, such as linear elastic and nonlinear fracture mechanics approaches for cracked tubular joints and members [52,55], and load cycle-by-cycle analyses for piles [56]. The approaches are complex. They are still under intensive development. It is not likely at this time (1987) that they can or should be incorporated into a general AIM approach at their present level of development. However, they can provide useful information in some special cases.

A viable approach for recognizing the effects of fatigue damage is that of determining how the capacity of the joint or brace might be reduced by fatigue cracking and other damage [52,57-61]. Analyses and experimental evidence can be used to assist such evaluations.

Inspections seem to provide the only reliable method of detecting fatigue damage [47,52,53], identifying the defects as cracks associated with this damage, and determining if the cracks are growing and leading to additional decreases in the element's capacity.

Projected decreases in the platform system capacity as a function of time (Fig. 12) can be used to guide definition of inspection intervals and consideration of alternative rehabilitation measures (and the timing of repairs). Uncertainties in fatigue effects can be recognized by injecting plausible changes in element capacities and stiffnesses as a function of time, and determining the resultant influences of these changes on platform capacity.

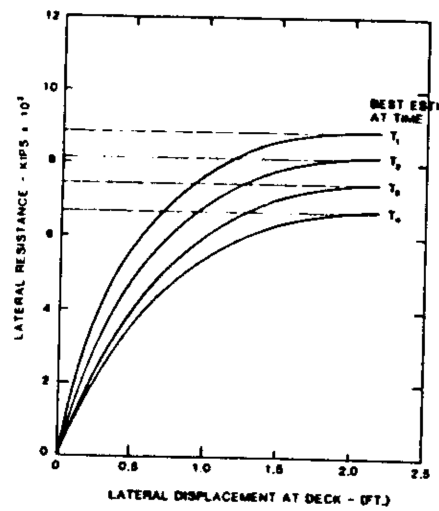


Fig. 12 Platform Capacity Decreases As A Function of Time Due to Fatigue Damage

RISK QUANTIFICATIONS

The approach used in this paper to quantify risk consists of three basic steps:

1. Based on a return period (RP) evaluation for the hazard of primary concern (e.g. hurricanes generating maximum wave heights, H_m) and a best estimate evaluation of the demand (e.g. total lateral force, S_m) associated with the range of the hazard, determine the return periods (likelihoods) associated with the potential demands (Fig. 9).

2. Based on the structure in its as-is condition, in the various conditions represented by practical AIM and rehabilitation measures, and in the various time periods of concern (reflecting potential fatigue effects), determine the best estimate and range of ULS resistances of the platform (R_c) (Figs. 10-12).

3. Determine the annual (A) and exposure period (L) risks (Pf_A and Pf_L, respectively) from

$$Pf_A = P(R_c \leq S_m) \quad (5)$$

$$Pf_A = (RP_c)^{-1} \quad (6)$$

$$Pf_L = L \cdot (Pf_A) \quad (7)$$

where RP_c is the Return Period (years) of the demands that exceed platform capacities.

The range of risks for the range of as-is conditions of the structure (Fig. 13), for various alternative strengthening or AIM measures (Fig. 14), and for various periods of time (Fig. 15) can be used to quantitatively evaluate alternative AIM programs.

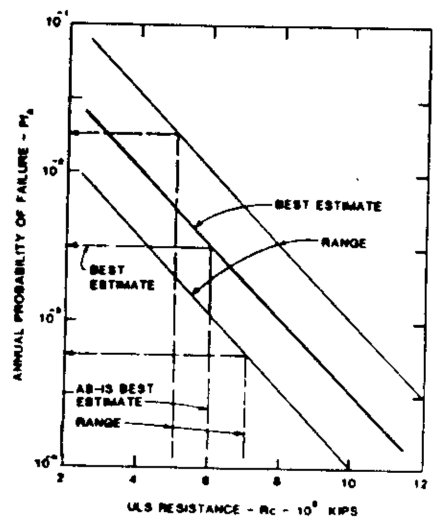


Fig. 13 As-As Condition Platform Risk

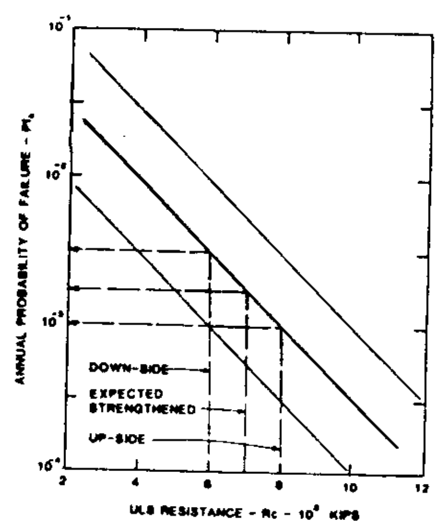


Fig. 14 Effect of Strengthening on Platform Risk

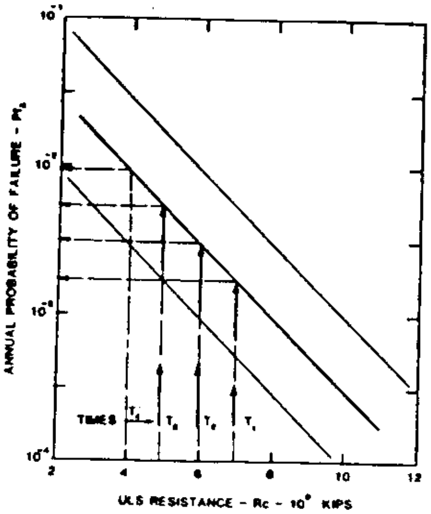


Fig. 15 Effect of Time (Fatigue Damage) on Platform Risk

EVALUATION OF AIM ALTERNATIVES

Evaluation of AIM program alternatives to determine the "best" program is basically a problem of determining the acceptable or tolerable level of risk associated with the platform operations, and the definition of a practical and affordable AIM program that will result in that level of risk. The level of acceptable risk is equivalent to an acceptable ULS resistance of the platform.

There are a wide variety of bases for determining what constitutes a tolerable level of risk. One is historical, i.e., the level of risk that has been developed by the industry and accepted by the public. The difficulty in equating actuarial (historical) and computed risks is twofold: (a) the data from which actuarial risks are derived are very limited (few failures), and (b) the information and analytical methods used to calculate risks result in approximations of the true risk (notional risk). Because quantified risks involve many approximations, they are only an index of the true risk.

Another problem is that the past risks may not be a valid basis to define acceptable future risks. Changing bases of engineering, construction and operations by the industry, and changing values of the public can make past risk bases invalid.

A second approach to defining an acceptable risk level is requiring that the structure be returned to its original or as-designed condition. In the case of platforms that were designed with unconservative criteria, the validity of such an approach is questionable. Similarly, if the platform were conservatively designed originally, then defects or damage need not necessarily imply that the platform risks are below an acceptable level.

A third approach is based on selection of an AIM alternative that attempts to optimize the use of resources, results in the highest possible utility, or develops the greatest present valued benefits associated with operations of the structure [1-3]. This approach is one that attempts to define the AIM program that results in a minimum total expected cost, $E(T)_O$, associated with AIM operations. The total expected cost, E(T) is taken as the sum of expected initial AIM costs E(I), and expected future loss of service costs, E(L):

$$E(T) = E(I) + E(L) \qquad (8)$$

The expected initial costs (Fig. 16) are all of those investments that are associated with implementing a particular AIM alternative. These costs could be those associated with strengthening, inspection, and operations changes intended to maintain or increase the platform capacity at some given level.

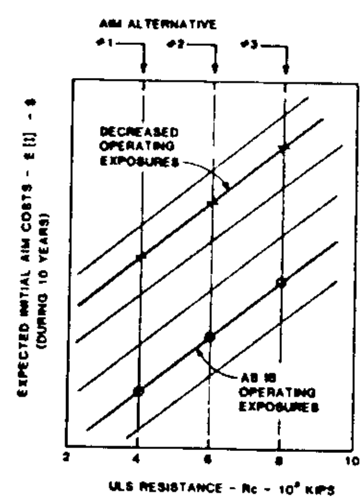


Fig. 16 Platform Initial A I M Alternatives Costs

In addition, initial costs could be associated with changing operations exposures (Fig. 16). For example, reducing onboard oil storage, requiring platform evacuations in advance of storms, and incrementing down-hole safety shut-in equipment can substantially reduce the costs associated with a loss of serviceability of the structure.

The expected costs associated with loss of serviceability (Fig. 17) can be computed as the product of the total costs given a loss of serviceability, C_f, the annual likelihood of the loss of serviceability, Pf_a, and the period of time being considered, L:

$$E(L) = (C_f) \cdot (Pf_a) \cdot L \quad (9)$$

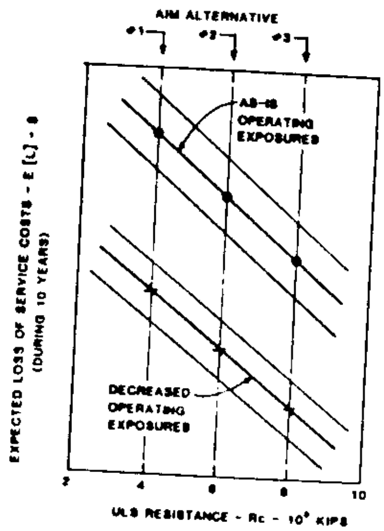


Fig. 17 Platform Expected Loss of Serviceability Costs

The loss of serviceability costs should include the expected value of all of those costs associated with the platform reaching its ULS at the point in time of concern. Such an estimate could be based on a replacement cost or on a salvage and abandonment cost (including the value of lost production or reserves).

Since short periods of time are of usual concern, it may not be necessary to consider present-valuing potential future costs associated with loss of serviceability.

Each AIM program can be associated with maintaining the platform at some ULS resistance for some period of time. The objective is to find the AIM program that develops a minimum total expected cost (Fig. 18).

It should be noted that the total expected cost associated with the AIM programs over the life of the facility must be such that the operations can be maintained at an economic level.

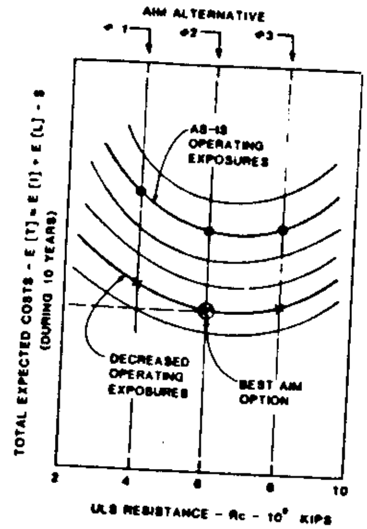


Fig. 18 Total Expected A I M Alternatives Costs

SUMMARY

The objective of this paper has been to outline an integrated, general, and non-prescriptive engineering approach to the requalification of existing platforms. Practicality, in the context of present engineering capabilities, was a key aspect in development of this approach. Keeping platforms in service and establishing their integrity at the least possible cost were key precepts.

Inspection, definition of defects and damage, and repairs and improvements must be given high priority in platform operations if structures are to retain high degrees of serviceability. Poorly maintained structures cost. It costs scarce resources to maintain structures. However, AIM investments can return significant dividends by increasing platform capabilities, lowering the incidence of serious down-time events, and lowering future repair costs. The benefits of AIM engineering and operations should be justified by the benefits that are achieved, and the resources that an operator can invest to keep a vital resource flowing to the market place.

The AIM approach is one of progressive reduction of risks to tolerable levels. The AIM approach proceeds in a step-wise manner through platform identification, a structure condition survey, screening of potential defects and the need for mitigation of these defects to determine the nature of and justification for alternative AIM programs. Once a particular AIM program has been chosen, it is engineered, implemented, and its results recorded as a basis for continuing the next AIM cycle.

Realistic analytical engineering models are a particularly critical element in any platform requalification. Realistic models are needed for characterizing the platform's future demands (loadings) and capacities (loading resistances). It is here that the best available current technology needs to be implemented. It is also here that site- and platform-specific factors may be injected into the analytical models. Of particular importance are the "experience factors." The experience factors pertain to knowledge of how a particular platform, or similar platforms, have performed in the past, especially in high loading (demand) situations. This up-dating information can serve as proof-loading or proof-capacity (resistance) data to assure reality of the analytical models results. It is important that conventional design-oriented analytical procedures and methods be re-examined, site/ platform-specific conditions recognized, and sources of implicit conservatism removed from the characterizations of future demands and capacities.

Uncertainties and the attendant risks are an important aspect of AIM processes and programs. A basic approach has been suggested to characterize platform demands, capacities, and performance. Broad scope AIM programs to manage uncertainties, risks and potential consequences are evaluated in the context of their costs and their benefits. These programs are implemented in a repetitive, continuing process of improving understanding and practices to lower risks associated with existing platforms.

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<u>Metric Conversion Table</u>

1 m = 3.28 ft
1 mm = 0.04 in.
1 m^2 = 10.76 ft^2
1 m^3 = 35.31 ft^2
1 kg m^3 = 0.062 lb/ft^3
1 kg = 2.20 lb.